Human Acceleration Studies

Bibliography—*Bates*
Terminology—*Clark, Hardy, Crosbie*
Acceleration Environments—*Hessberg*

National Academy of Sciences – National Research Council

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Panel on Acceleration Stress
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FOREWORD

Among the urgent research and development problems considered by the Panel on Acceleration Stress were those related to exchange of information. In two areas efforts were made to improve the situation. The first problem had to do with the large volume of work which is being done in laboratories of Industry, Government and in Universities which is being held to rather limited distribution. Much of this work is of interest to the entire scientific audience in the acceleration field and the question arose as to how to make this information more accessible. The Panel undertook to study the problem of report distribution and indexing with the idea of more clearly defining the areas of interest and of providing a means of classifying and identifying the published work in the acceleration field. The results of this study are contained in the proposed index for reports which has received informal approval of the investigators who made up the Panel on Acceleration Stress. As a second part of the communication problem, the need for an acceptable uniform terminology to specify the force inputs and the reactive forces in the body was recognized. To meet the requirements in this area the Panel has suggested the adoption of the NASA standard aircraft terminology to describe the force inputs and a second closely related physiological terminology to describe the reactive forces or displacements. The usefulness of these two studies may lie not so much in the adoption by all investigators of the recommendations as in pointing out clearly the problems and their importance in acceleration research and development.

Included with these two general studies is a review of the present concepts of the acceleration problems which planned space programs impose. Although the specific vehicles may be changed as designs become more firm, the general problems of the next decade of Aerospace Medical Research and development will probably remain as stated in the third of these reports.

JAMES D. HARDY
Chairman, Acceleration Panel

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A BIBLIOGRAPHIC INDEX FOR CATALOGING THE ACCELERATION LITERATURE

By

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National Aeronautics and Space Administration

Acceleration Classification Index

As a considerable volume of literature on acceleration research is now available with more literature being generated at an increasing rate, the Panel on Acceleration Stress believes that it is highly desirable for such information to be indexed and catalogued in a uniform manner so that pertinent information can be readily located by users. Various abstracts of acceleration literature are now available; however, most of these use an open-ended, non-systematic indexing system, so that the user must scan all of the reports in order to find desired references. This index is offered as a solution to that problem.

I. Vibratory

II. Impact

III. Sustained Linear

IV. Sustained Angular

V. Zero G and Subgravity

VI. Weightlessness

  A. Review and Summation Papers

  B. Research Facilities, Equipment, and Instrumentation

  C. Research Techniques

  D. Training

  E. Pathology

F. Performance Capabilities of Organism

G. Physiological Effects on
   1. Cardiovascular System
   2. Digestive System
   3. Muscular System
   4. Nervous System
   5. Respiratory System
   6. Skeletal System
   7. Special Sensory Organs
      a. Ear
      b. Eye
   8. Other Systems and Organs

H. Psychological Effects on
   1. Psychomotor Performance
   2. Sensory Perceptions
   3. Spatial Orientations
   4. Cognitive Functions

I. Tolerance of Organism (Level and Duration)
   1. End Points
   2. Effects of
      a. Protection and Body Support
      b. Drugs
      c. Environment
         (1) Atmospheric Composition
         (2) Light
         (3) Noise
         (4) Pressure
         (5) Temperature
         (6) Others
      d. Medical History
      e. Muscular Control
      f. Nutrition
      g. Acceleration-Time Pattern
      h. Physiological Changes
      i. Posture
      j. Psychological Factors
      k. Accumulative Effects

J. Physical Responses and Characteristics of Test Subject

E. Pathology covers papers on the effects of acceleration on tissue pathology.

F. Performance Capabilities covers reports on the effects of acceleration on the subject's ability to perform his assigned functions. It specifically covers a pilot's ability to control his vehicle while he is subjected to acceleration forces.

G. Physiological Effects covers reports on the effects of acceleration on the primary body systems.

H. Psychological Effects covers such matters as sensory illusions, body orientation, and the overall effects of acceleration on psychomotor performance.

I. Tolerance covers the ability of the subject to withstand acceleration and the effects of various environmental conditions, drugs, and general body tone on the ability to withstand acceleration.

J. Physical Responses and Characteristics covers the overall physical response of the body of the subject to acceleration forces.

It is expected that many papers on acceleration research will fall under several of the above headings. Nevertheless, it is believed that this indexing system will allow quick acquisition of information on acceleration research in specific areas. This index is not intended to supplant the Index Medicus but rather to provide a specific system tailored to the primary users. It is suggested that an author, in preparing a paper on acceleration research, index his paper according to this system and that he indicate the indexing by both number and word description in his abstract. This would maximize the usefulness of such an indexing system and would allow the author to insure that his paper was correctly indexed.

To illustrate the application of this system, the abstracts on three papers on acceleration research and their coding by this indexing system are given below:

NASA TN D-337, "Centrifuge Study of Pilot Tolerance to Acceleration and the Effects of Acceleration on Pilot Performance." The experimental set-up consisted of a flight simulator with a centrifuge in the control loop. The pilot performed

his control tasks while being subjected to acceleration fields such as might be encountered by a forward-facing pilot flying an atmosphere entry vehicle. Information was obtained on the combined effects of complexity of control task and magnitude and direction of acceleration forces on pilot performance. Boundaries of human tolerance to acceleration were established. A comparative evaluation was made of the three-axis type of side-arm controller and the two-axis type in combination with toe pedals for yaw control.

III. Sustained Linear
- F. Performance Capabilities of Organism
- I. Tolerance of Organism (Level and Duration)
    - 2. Effects of
        - a. Protection and Body Support

NASA TN D-345, "Physiological Effects of Acceleration Observed During a Centrifuge Study of Pilot Performance." An investigation was conducted by the NASA Ames Research Center and the NADC Aviation Medical Acceleration Laboratory to study the effects of acceleration on pilot performance and to obtain some meaningful data for use in establishing tolerance to acceleration levels. The flight simulator used in the study was the Johnsville centrifuge operated as a closed loop system. The pilot was required to perform a control task in various sustained acceleration fields typical of those that might be encountered by a pilot flying an entry vehicle in which he is seated in a forward-facing position. A special restraint system was developed and designed to increase the pilot's tolerance to these accelerations.

III. Sustained Linear
- G. Physiological Effects on
    - 1. Cardiovascular System
    - 5. Respiratory System
    - 7. Special Sensory Organs
        - b. Eye
- I. Tolerance of Organism (Level and Duration)
    - 2. Effects of
        - a. Protection and Body Support
- J. Physical Responses and Characteristics of Test Subject

NADC-MA-5005, "The Effect of Temperature on Tolerance to Positive Acceleration." With the advent of space flight, the problems associated with the physiological effects of extreme temperatures may become a critical factor relating to pilot performance under conditions of high acceleration. In order to determine the effects of high environmental temperatures on G tolerance, six trained centrifuge subjects were exposed to positive acceleration in the heated gondola of the Johnsville centrifuge. Seven thermocouples were located at strategic places over the body surface in order to obtain an accurate recording of skin temperature. Although humidity was not controlled, it was recorded during all centrifuge runs. The environmental temperatures studied ranged from 75°F to 160°F where a decrement in G tolerance of 1 G has been obtained at the upper temperature range.

III. Sustained Linear
  F. Performance Capabilities of Organism
  I. Tolerance of Organism (Level and Duration)
    2. Effects of
      c. Environment
        (5) Temperature

A PROPOSED PHYSIOLOGICAL ACCELERATION TERMINOLOGY WITH AN HISTORICAL REVIEW

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Summary

A physiological acceleration terminology is proposed.

1. The unit for physiological acceleration shall be G to distinguish this acceleration from the "true" displacement acceleration, generally designated by aerodynamicists with the unit g. The physiological acceleration represents the total reactive force divided by the body mass, and hence includes both displacement and resisted gravitational acceleration effects.

2. The physiological acceleration axes represent directions of the reactive displacements of organs and tissues with respect to the skeleton. The Z axis is down the spine, with $+G_z$ (unit vector) designations for accelerations causing the heart, etc. to displace downward (caudally). The X axis is front to back, with $+G_x$ designations for accelerations causing the heart to be displaced back toward the spine (dorsally). The Y axis is right to left, with $+G_y$ designations for accelerations causing the heart to be displaced to the left. For accelerations in which effects on the entire body are of concern, the origin of the axes shall be half way between the anterior (craniad) surfaces of the iliac crests, with the Z axis passing from the midpoint between the suprasternal notch and the dorsal surface of the dorsal spine of the last cervical vertebra to this origin. The X and Y axes are mutually perpendicular to this Z axis.

For acceleration effects on the vestibular apparatus, the origin of the head axes shall be the midpoint between the external auditory meatuses (on the Y axis), with the X axis passing from the ventral medial margin of the nasal bones through this origin.

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3. Angular accelerations which cause the heart to rotate (roll) to the left within the skeleton shall be specified by the $\dot{R}_x$ unit vector, representing radians/sec.^{2} about the X axis. Angular velocities in the same sense shall be specified by the $+R_x$ unit vector, representing radians/sec. about the X axis. Similarly, $+\dot{R}_y$ represents pitch down of the heart within the skeleton, and $+\dot{R}_z$ represents yaw right of the heart within the skeleton.

4. Linear acceleration environments may be represented by the three acceleration components (along the G_x, G_y, and G_z unit vectors) or by a resultant acceleration and the azimuth and altitude angles of the resultant with respect to the body axes. Azimuth is measured from the +X axis (to the back), with positive rotation clockwise as seen from above. Attitude is measured from the horizontal (XY) plane, with positive angles when in the hemisphere of the +Z axis (downward). Thus a man reclining in a chair tipped back 45^o is experiencing 0.7 G_x and 0.7 G_z, or $1G/0^o$, 45^o.

5. Whenever rotations accompany linear accelerations, the reference point for the linear accelerations should be specified, and the time histories of the angular velocities and angular accelerations should accompany the time histories of the linear accelerations, to allow the computation of linear accelerations at other points.

This proposed physiological terminology is compared to other acceleration terminologies, with a partial tracing of origins in the literature of certain acceleration terms.

I. Introduction

This report is an expansion of previous reports on this same topic (Clark and Crosbie, 1959; Hardy and Clark, 1960), particularly with the addition by the first author of the bibliographic origins of certain acceleration studies and concepts.

It was notably in the decade prior to the beginning of the Second World War that acceleration as a physiological problem came to the attention of flight surgeons. The problem centered principally about the fact that pilots, in executing certain maneuvers, suffered impairment of vision. This involved loss of the peripheral visual field or complete loss of vision, and occasionally the development of unconsciousness. As this situation was unacceptable, it became a task for the flight surgeon to develop some means by which the pilot could be protected from these effects of acceleration. It is perhaps for this reason that positive G or the displacement of the heart and the blood toward the feet became the standard type of acceleration subject to investigation by the flight surgeon and his associated physiological team.

Figure I* shows a diagram of some simple or typical military aircraft maneuvers involving accelerations of the type just mentioned. At the top is a 180^{o} turn with the development of positive G between 2 and 5 G for 35 seconds. In the center is a pull-up from a 70^{o} dive with positive acceleration from 4 to 6 G for 1 to 3 seconds. The lower figure shows a pushover into a dive with the development of so-called negative G for a period of about 1 to 2 seconds. It was these types of maneuvers and the resulting accelerations that concerned the flight surgeon during most of World War II. In fact, most of the human centrifuges were built for the purposes of studying the effects of positive acceleration and devising means of combating the impairment of vision and unconsciousness which might develop from exposure of the pilot to these accelerations. As long as the investigations of the effects of acceleration stress were confined to such simple types of experiment, there was little or no confusion resulting from the use of local laboratory terminology to specify the type of acceleration being received by the subject of an acceleration experiment. Thus, "positive G" was

* Figure I is from Lombard, 1951.

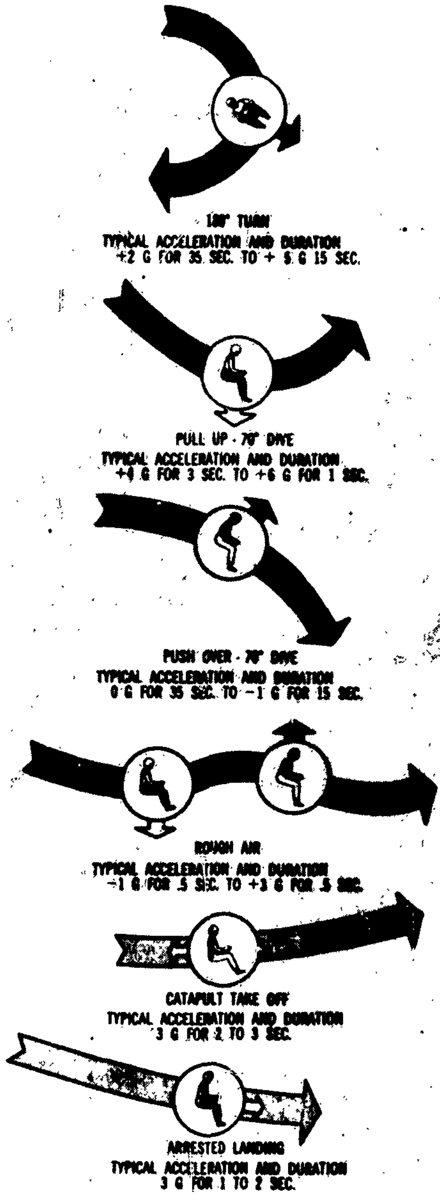


Figure I. Typical military maneuvering accelerations.

well understood to involve the displacement of the heart toward the feet, and "negative G" the reverse situation. There were a few instances in which one might speak of "prone G" involving the displacement of the heart towards the chest, and "supine G" which was the reverse situation in which the heart is displaced toward the back. However, with these simple terms one could adequately describe all of the accelerations which were of importance in the early experimental work on acceleration. It was not that the physiologist and the flight surgeon did not recognize that the pilot might be subjected to more complicated types of acceleration but rather that these had not yet been proved to be of operational importance. However, with the development of high-speed aircraft, the problem of ejection from these aircraft to provide a safe escape, presented a different type of problem than that which had been encountered previously. This was due principally to the fact that during the period of escape the pilot was very likely to tumble as well as to slow rapidly under the considerable amount of dynamic pressure of the air. This presented the aeromedical investigator with an entirely different type of problem, and it was toward the solution of this problem that the centrifuge of the Aviation Medical Acceleration Laboratory of the U.S. Naval Air Development Center, Johnsville, Pa., was originally directed.

Figure II shows a photograph of the interior of the centrifuge chamber of this Laboratory showing the large 50-foot arm together with the gimbal system by which the gondola containing the subject

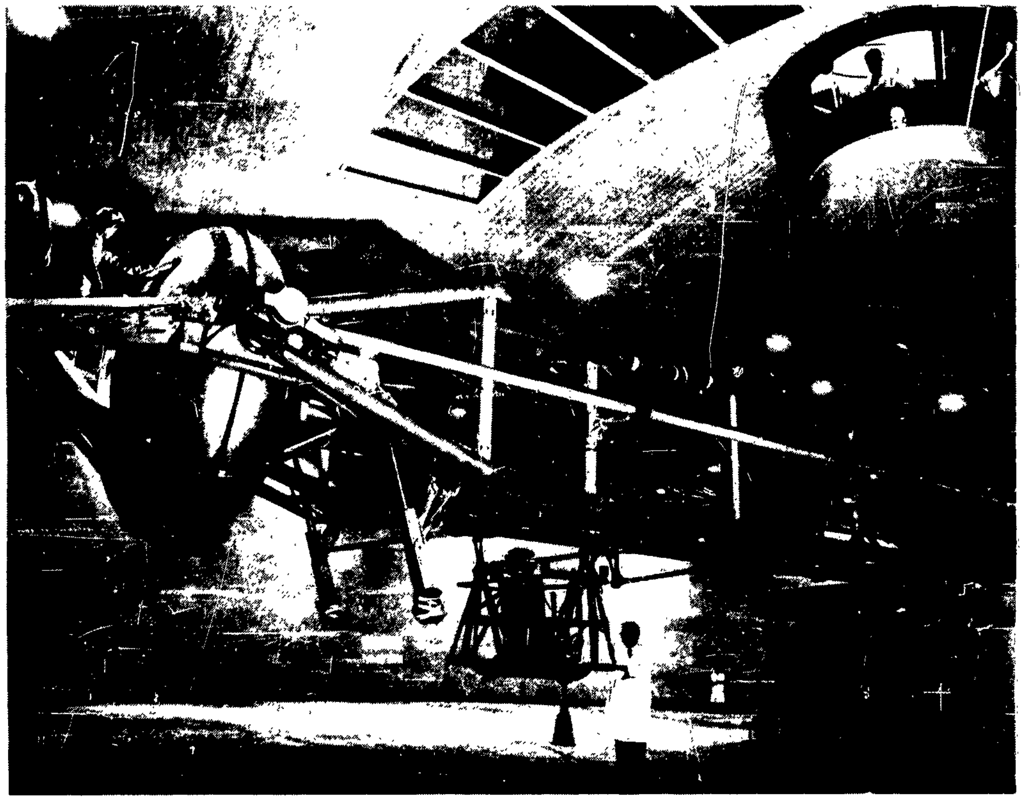


Figure II. Centrifuge chamber, Aviation Medical Acceleration Laboratory.

may be rotated about two axes independently. It was the conception of the engineers and physiologists who designed this laboratory that this machine would be capable of simulating the escape accelerations encountered by the pilot upon ejecting from high speed aircraft. A novel feature of this centrifuge was its control, which was planned to be entirely automatic and carried out by means of a series of cams which would control in synchronism the rotation of the centrifuge arm and the rotation of the gondola about its two axes. The introduction of automatic control meant that the physiologist was faced with the necessity of specifying exactly the accelerations which he expected to program in terms of both angular and linear modes. This requirement, of course, necessitated bringing the mathematician and the physicist into the problem of how to present the acceleration vectors to the subject in a way which would be a realistic simulation of the situation met in an ejection seat problem. It was recognized that the Johnsville centrifuge, with only three degrees of freedom of control, could accurately simulate only three of the six degrees of freedom of flight. Usual emphasis has been on the

linear accelerations, to provide an approximately correct force environment. Hence by necessity, the centrifuge provides angular motion "artifacts" which do not occur in flight. In order to prepare a series of cams which would carry out physiological experiments, the physicist and the mathematician had to know in detail both the angular and the linear accelerations which were necessary to make up the desired acceleration pattern. Fortunately, this was not an impossible problem in analytic mechanics, and the aeronautical engineer who had been working for many years with these vectors was able to supply a framework to describe the accelerations experienced under many conditions of flight. Fortunately also, the flight surgeon and the physicist had been working together reflecting on the forces acting upon man in flight, and a monograph on the subject was published by the U. S. Naval School of Aviation Medicine (Dixon and Patterson, 1953).

The calculations and machine shop work involved in making the sets of centrifuge control cams were so tedious that only a few experimental programs were actually carried through in this manner. Figure III shows the acceleration patterns required for the last of these programs, a simulation of the re-entry acceleration patterns expected to be encountered by the X-15 research aircraft under certain emergency conditions (Clark and Woodling, 1959). The final

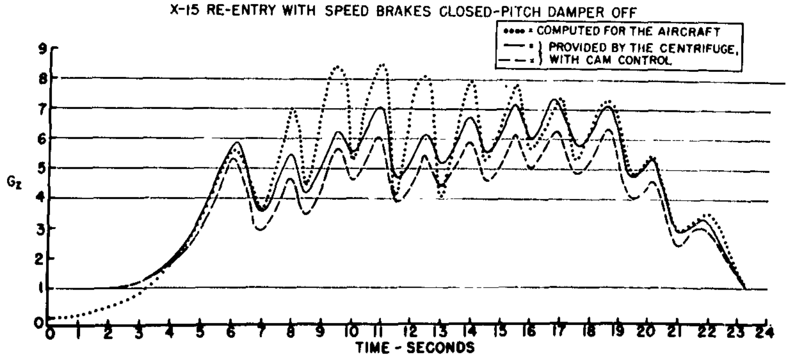


Figure III. Acceleration Patterns

shaping of the cam profiles was carried out by hand after an initial approximate computer design and the subjects were tested for their tolerance to these accelerations. The solid and dashed lines in the figure indicates the experimental simulations of this acceleration pattern as tested on the X-15 test pilots. To obtain a better idea of the centrifuge control problem involved, Figure IV shows an acceleration cam of the type employed in most of the previous acceleration studies on the Johnsville centrifuge, and the sawtoothed cam which was required for the particular study for the X-15 research aircraft.

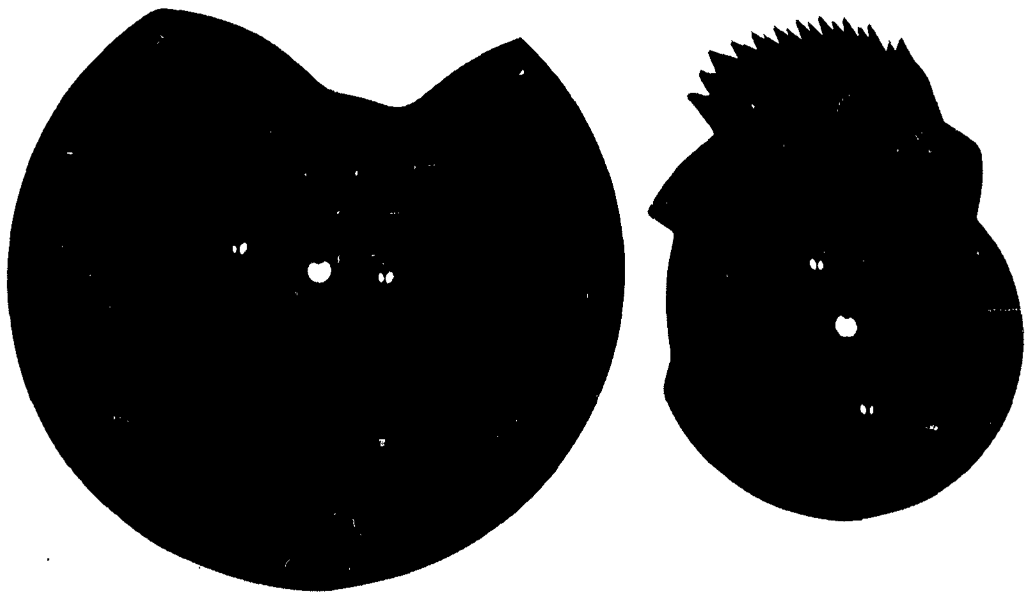


Figure IV. Acceleration Cams.

It was quite evident from the X-15 study that the matter of control of the centrifuge and of the specification of accelerations was entering a new phase, one to which flight physiologists would have to become accustomed. Figure V diagrams the pilot seated in the gondola and facing his instruments, controlling his flight mission by actuating controls. These controls are connected to a high-speed computer upon which are programmed the dynamic characteristics of the aircraft, of the control system, and of the instruments' responses. The centrifuge is also connected to the computer through a coordinate conversion system providing a means by which the centrifuge is made to respond in such a way as to give accelerations to simulate those which would have been encountered in actual flight. Thus, this system provides a type of simulator which is similar in every respect to those which are used in advanced aircraft design but with the addition of accelerations to the simulation. The pilot is thus able to experience the forces of flying a new aircraft or space vehicle, and determine its responses to his controls, before the vehicle is built, or before it has been flown in the manner proposed. This aspect of acceleration research has become so important that many new accelerators are being adapted for control by computers.

One may thus summarize the centrifuge problem briefly as follows: First, there is the requirement to program complex

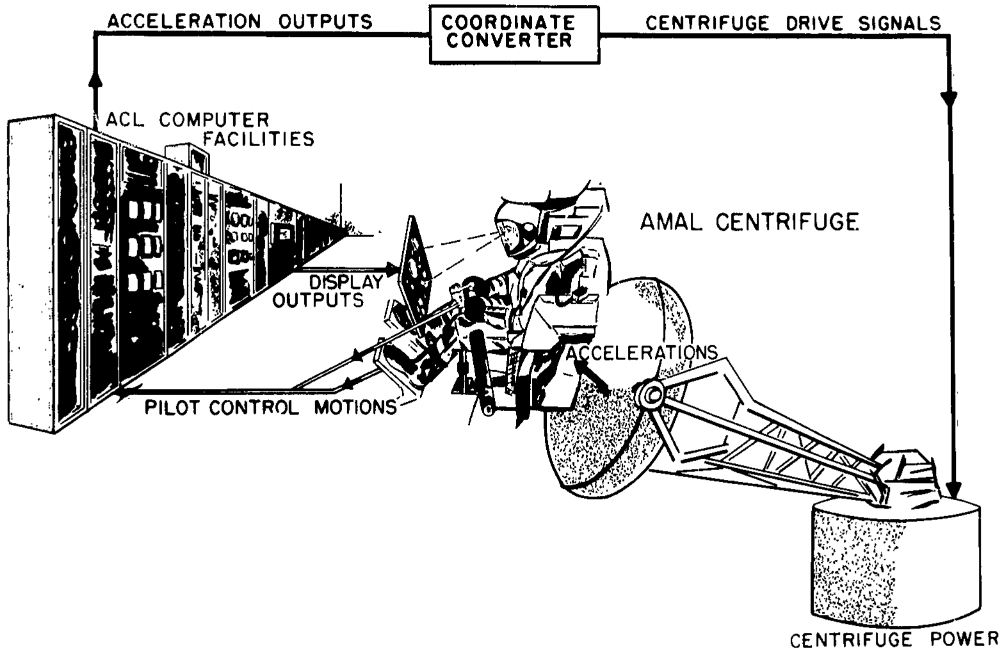


Figure V. Closed loop centrifuge operations.

patterns of acceleration which include resultant accelerations not only along the usual body axes but also accelerations which vary both in direction and in magnitude. Second, the best way to effect the control of the centrifuge in response to pilot control motions is to adapt the centrifuge for automatic control by electronic means--in short, computer control of the centrifuge is required. Third, a standard terminology for acceleration is required, a terminology which provides the mathematical description of the acceleration environment referred to some convenient point, such as a point within the man. This description of the acceleration environment determines the readout of the computer system in terms of the voltages which are applied to the control system of the centrifuge or other acceleration device. It is clear that terms such as "positive G," "negative G," "supine G," "prone G" and so forth cannot be used by the computer engineer to program the accelerations for centrifuge studies. The computer engineer and mathematician must use a quantitative terminology which can be converted rapidly to computer language for the control of human acceleration devices.

II. The Development of Acceleration Studies

Galileo (about 1609) showed that the velocity of falling freely was proportional to time, and the distance of falling to time squared. Huygens (1673) determined the acceleration of gravity by means of

pendulum observations, and showed that centrifugal acceleration is proportional to the square of the angular velocity and inversely proportional to the radius. He explained the decreased acceleration of gravity at the equator in terms of the increased centrifugal force of the earth's rotation at the equator. "Newton's law of gravitation" which we now write in the form

$$F = G\frac{Mm}{r^2}$$

in which G is the gravitation constant, was expressed by Newton (1687) in parts (Mach, 1942), not in the composite equation; the symbols g or G do not appear in Newton's work, or in Bouguer's, (1749) in which the period of a pendulum is determined at various altitudes in Peru, or in Maskelyne's (1775) in which the gravitational effect of a mountain is determined, or in Cavendish's (1798) in which the attraction of two known masses is measured. In Kater's work in 1819, on the variation in length of a pendulum of two seconds period, g stands for the distance of body falls in one second. Baily, in 1832, reporting on the effect of operating a pendulum in a vacuum, speaks of the force of gravity but does not use g. Airy, in 1856, in studying pendulum rates at the top and bottom of a mine, uses g for gravity of the external surface of the shell of earth, and G for gravity of the internal surface of the shell, at the bottom of the mine. Context indicates that these symbols are for the acceleration of gravity. Pratt, in 1856, uses G for the force of local attraction, with components V vertical and H horizontal. More recently, Poynting, in 1891, reports studies of both G, the gravitational constant, and g, the acceleration of gravity. We have not yet established who first used these in the modern sense. Ambronn reviews the many determinations of these constants.

When a body is displaced under acceleration, inertial forces act as if a component of the body weight proportional to the ratio of the displacement acceleration to the acceleration of gravity acts along the displacement acceleration vector. We assume that the physiological effects of a displacement acceleration and of gravitational attraction without displacement, of equal magnitude, are equivalent. It is common practice to speak of a resultant acceleration vector, having the direction of the resultant force or weight of the mass being acted upon, combining the displacement and resisted gravitational effects. We do not yet delineate biological problems in the still theoretical studies of the rate of transmission of gravitational effects if matter is abruptly converted into energy, or if matter is travelling with nearly the speed of flight.

Some of the landmarks of human flight and exposure to acceleration are traced in Section III. It is interesting, in our "rocket era" to see history repeating, concerning the political objections to flight and high speed travel. Thus Samuel Johnson wrote, presumably after an early balloon accident, "The fate of the balloon I do not much lament, to make new balloons is but to repeat the feat again.... The first experiment, however, was bold, and deserved applause and reward, but since it has been performed and its result is known, I had rather now find a medicine that can cure an asthma," (Thorpe 1918). The "Quarterly," commenting on Stephenson's new railroad in the 1820's, wrote "What can be more palpably absurd and ridiculous than the prospect held out of locomotives travelling twice as fast as stage coaches? We would as soon expect the people of Woolwich to suffer themselves to be fired off upon one of Mr. Congreve's ricochet rockets as trust themselves to the mercy of such a machine going at such a rate," (Marshall, 1933). Stephenson thereupon named his locomotive "The Rocket," and indeed attained 36 mph. The military flyer should note John Paul Jones (1778): "I wish to have no connection with any ship that does not sail fast, for I intend to go in harm's way," (Naval Aviation News, February 1961). After Langley's airplane model flew in 1896 a reporter asked, "But will it not be impossible to induce people to risk their lives on the first experiments on such machines?" "I think not," replied Mr. Langley. "If I had a large aerodrome constructed on the principles of the one you have seen today though the danger of the initial experiment would undoubtedly be great, I am sure I would have to turn away any number of men who would risk a flight upon it," (Anon. 1897). By 1910 an editor commenting on the increasing number of fatal accidents at flying exhibitions during record attempts, warned that if speed depended on the amount of safety sacrificed, then such records were not true progress (Anon. 1910).

Early human centrifuge work (see Gauer, 1950) involved manual power, and less than 5 G. Interestingly, Mach (1875) detected what we now call the oculogravic illusion in a railroad train going around a corner as well as on his centrifuge. Hill and Bernard (1897), studying the effects of body position at 1 G on circulation, clarified important aspects of the physiological responses to acceleration, including effects of an abdominal support or belt. Maxim, seeking financial support for his airplane work, developed the "round about" or captive flying machine, essentially an airplane attached by wires to a central axis about which it rotated, for rides by the populace, at about the time that a similar device was invented in the United States (Maxim, 1908). All the aerodynamic controls were removed at the request of the London County Council, after observing the effects on these machines of gusts. Dr. A. P. Thurston,

Maxim's engineer and designer, was given a ride in the first machine at the Crystal Palace in 1903. He reached 6.47 G and collapsed unconscious to the bottom of the car, evidently the first human to be made unconscious by centrifugation (Thurston, 1952).

The early airplanes were of such fragility that drag air loads would break the wings when diving speed became excessive (Anon., 1910), without maneuver loads. The planes were strengthened, and, as indicated in Chapter III shows, maneuvers were developed in this period. The then astounding intentional lateral control to bank on corners first used in public by the pilot of the Wright biplane in the race at Nice in 1910 opened a new era of "coordinated" maneuvers (Hamel and Turner, 1914). Zahm (1911) calculated the loads due to "curvilinear and fancy flight," but coordinated turns with a bank angle of 60^o, giving a 2 G_z resultant, were still to be flown (Zahm, 1913). Zahm (1911b) suggested an accelerometer design, but such a device was evidently not built for another five years.

"Factors of safety" and "limit load factors" became emphasized in this period. Zahm (1911b) describes loading an inverted wing of the Curtiss hydroplane, with sand, to have parts break at 10 to 30 times the normal load. "Tension tongs" were developed to determine the tensions in the wing struts (Zahm 1911b). Experiences in 1913 showed the German Aviation Corps that their airplanes did not have the strength necessary for the safety of aviators (Hoff, 1922). The Germans held an accelerometer design contest in 1914, but it was not concluded due to the war, and airplane designs were based on studies of wire tensions. Maneuvers were found to involve 2 G; the aircraft were built with a factor of safety of three times, hence to be capable of 6 G if all parts met specifications. Ultimate load before the airplane would break completely was to be another two times or 12 G total (Hoff, 1922).

Aircraft stability affects the rate at which maneuver loads may be established. The Wright aircraft were unstable in the sense that they required constant attention on the controls to maintain level flight (Green, 1918), and early attention was directed to increasing stability. Apparently the Germans were quite successful in this, utilizing Prandtl's aerodynamics designs, for their 1914 flight maneuvers did not exceed 2 G. But too stable an airplane gives too heavy a control, and too insensitive a response. The early French airplanes on the other hand were evidently more unstable and hence highly maneuverable, giving them an initial advantage in "dog fights" early in the war--if the wings didn't come off. By 1918 maneuver loads had increased to over 4 G.

Alder, in a chapter entitled "Some Notes on the Medical Aspects of Aviation" in the book by Hamel and Turner (1914), states, "The use of abdominal belts is certainly a thing to be advised, because it keeps up the tone of the splanchnic areas and so guards against any sudden attack of fainting." But aviation medicine works of this decade do not emphasize linear acceleration effects. Angular acceleration effects, and the sense of orientation, are on the other hand, given great prominence. Anderson (1919), for example, does not discuss maneuver loads, nor does Bernard (1918), nor does the (United States) Air Service Medical Manual (Anon., 1918). This work does mention unconsciousness in stating what selection is <u>not:</u> "Another much rumored test was described as follows: When the applicant least expected it, he would be hit over the head with a mallet and if he regained consciousness within 15 seconds he was qualified as being of the stuff of which aviators are made." This work notes that only 2 per cent of the fliers lost to service are put out "by the Hun," 8 per cent by airplane malfunctions, and 90 per cent by failures of the pilots--that is, if he had done something differently, and seemingly within his power, he might have survived. The "Ruggles orientor" is pictured, a cockpit within three power driven concentric rings, a device used for early ground based flight simulation. (Earlier "flight simulation" included sitting in the airplane cockpit when on the ground, and working the controls. Prior to his inverted flight in 1913, Pégoud sat in the cockpit of his aircraft, inverted on trestles wearing shoulder straps, to simulate $-1\ G_z$.) (Anon., 1913)

Head (1919), in a reference given inadequate attention in aviation medicine textbooks, described the report of Major V.B., "After an unsuccessful attempt to discover the smallest horizontal banked circle in which a Sopwith triplane could be spun, he got the machine into a turn at 3,000 feet. On starting the second turn 'the sky appeared to go grey.' 'A mist gradually arose like going under an anaesthetic,' and he 'fainted.' It was not an unpleasant sensation. When he came to himself, he was flying over a village about a mile away from the place of the experiment. The unconsciousness must have lasted about 20 seconds. During the first turn g reached 4.5, during the second, 4.6. The turn was of about 140 feet at a speed of 114 miles an hour. This pilot found experimentally that whenever the acceleration (g) was pushed up to a high figure, he experienced the characteristic darkening of the sky which was preliminary to fainting. On another occasion he was looping and diving a D.H. 4 during a mock flight when these preliminary sensations reappeared. He realized his danger and struggled against losing consciousness. First came a feeling of pressure in the head; then a mist gradually approached and spots rose before his eyes. He felt faint, chiefly

at the bottom of the loop, and was quite conscious at the top. Then 'daylight' returned during the dive, and he came down about three minutes later feeling perfectly well. This preliminary sensation is distinctly pleasant, but is associated with inability to make an effort, 'it requires a definite struggle to right the machine.'" Head however interprets his cases of "fainting" in the air (where anoxia is not a factor) as being vestibular in origin. Head's "case 4" was testing an S. E. 5, when he "fainted" at about 5,000 feet. "Everything seemed to go black all at once." The term "blackout," however, is not used. Davies (1920), referring to these same cases, speaks of the importance of vascular tone in preventing the blood from gravitating to dependent parts.

Broca and Garsaux (1919), in attempting to understand an accident case, centrifuged dogs to 98 G for 5 minutes. They found anemia of the brain and congestion at the bases of the lungs and extreme generalized congestion of the abdomen, with the dog killed at 98 G but another surviving 80 G. They emphasized the probable advantages of aviators wearing an abdominal band. They felt that the "coefficient de sécurité" of airframe design was too low, for pilots might survive more stress than the airplane. This controversy of how far beyond human tolerances vehicles should remain intact is still very much with us, particularly now that we recognize that "tolerance" is affected in major ways by the form of body restraint and the extent that body distortions are minimized (Clark and Gray, 1959). Framme (1931), for example, felt that 4 G was the "critical acceleration" for airplane design. Clément (1918) also centrifuged animals (and eggs, embryos, and plants) to interpret effects, showing blood displacements (dehydration) and, alternately, special forms of compression.

The first accelerometer built and used in flight, from 1917 on, was apparently that of Searle (Searle and Lindemann, 1917; Searle and Cullimore, 1918). It consisted of a glass or quartz fiber of about 0.01 min. diameter bent in the form of a semi-circle of radius 1.3 cm and clamped on a block at the base of the semi-circle. Light from a lamp is focused on the free "vertex" of the semi-circle, which is imaged on a slit. Deflections of the free edge of the semicircle due to acceleration cause deflections of the image which are recorded on photographic paper, with a sensitivity of 0.25 to 0.4 cm/G. The acceleration of various flight maneuvers, including "dog fights" (to 4.2 G) and flight through turbulent air, are shown. They speak of their readings as "accelerometer ratios" to emphasize that they are not true displacement accelerations, but include gravitational effects.

Zahm (1919) described an "airplane shock recorder" consisting of a line of styli loaded with springs of increasing tensions, and showed its use. Norton and Allen (1921) made an improved linear accelerometer consisting of a flat steel spring supported rigidly at one end, with its motion damped electromagnetically. Norton and and Warner (1921) compare this device to the Searle accelerometer. Reid (1922a) described the NACA three-component accelerometer, and Reid (1922b) described angular velocities and accelerations of flight. Norton and Carroll (1923) and Dearborn and Kirschbaum (1930, 1931) record aircraft maneuvers, the last including a pull-up of 9.3 G, but do not mention physiological effects. These last authors mention X, Y, and Z axes, but missed the opportunity to establish terminology by not emphasizing a terminology. One finds from their tables that they considered longitudinal acceleration positive when air speed was decreasing (on a pull-up), in disagreement indeed with the NACA vehicle terminology. They do not emphasize separation of displacement and resisted gravitational accelerations, as do Searle and Cullimore (1918).

The physiological effects of airplane maneuver accelerations became more widely recognized at the Pulitzer trophy race of 1922, when Lt. R. L. Maughan reported brief unconsciousness when making the high speed turns around the pylons, and at practice flights at 250 mph at the Pulitizer race of 1923, when Lt. "Al" Williams reported that he "passed out completely" on a turn (Dowd, 1931). Bauer (1926) ascribes these effects to blood displacements into the easily dilated splanchnic vessels and lower extremities, but he does not discuss the acceleration magnitudes involved. Similar reports of dimming of vision and confusion on rounding pylons came from pilots in the Schneider trophy races of 1929 (Fulton, 1948).

Doolittle (1925), in a work which unfortunately is rarely referenced in aviation medicine textbooks, systematically explored these physiological effects. "The maximum acceleration which a pilot can withstand depends upon the length of time the acceleration is continued. It is shown that the pilot experiences no difficulty under the instantaneous accelerations of 7.8 g, but that under accelerations in excess of 4.5 g, continued for several seconds, the pilot quickly loses his faculties. While this is disconcerting to the pilot, it is not necessarily dangerous for one in good physical condition unless continued for a period of 10 to 12 seconds." After doing power spirals at "4.7 g," he notes, "After the steady condition was reached the pilot gradually began to lose his sight, and for a short time everything went black except for an occasional 'shooting star' similar to those seen when one is struck on the jaw. The pilot appeared to retain all facilities except sight, and no difficulty was

experienced in righting the airplane. Sight returned almost immediately when the acceleration was decreased to normal by restoring the airplane to a condition of steady level flight."

Doolittle continues, "The effect of this maneuver on the pilot is not particularly uncomfortable. The sensation is that of having a tight band around the forehead and a feeling that the eyeballs are about a half an inch too low in their sockets." This indeed may be the origin of the "eyeballs down" acceleration terminology referred to below. "From the results of these tests it is apparent that serious physical disorders do not result from extremely high accelerations of very short duration, but that accelerations of the order of 4.5 g continued for any length of time result in a complete loss of faculties. This loss of faculties is due to the fact that the blood is driven from the head, thus depriving the brain tissues of the necessary oxygen. To the pilot it seemed that sight was the only faculty that was lost." Apparently Doolittle did not experience unconsciousness in his work. Doolittle had "balanced" control surfaces on his airplane, which allow large deflections to be made rapidly with little control force. He says, "It would follow that if the airplane were suddenly pulled out of a dive at a speed in excess of 185 mph (and which would frequently occur in actual combat with this airplane), the wings would fail. It was this consideration which caused the engineering division of the Air Service to require a factor of 12 at high angles of attack for pursuit airplanes and to recommend against the use of balanced controls on that type." The Fokker PW-7 pursuit airplane he was using had a dynamic load factor of 8.5, that is, maneuver loads of 8.5 G_z would just not cause damage to the structure.

In 1927 Luke Christopher reached 10.5 G_z on an abrupt pull-up at 173 mph in the Navy F6C-4 Curtiss "Hawks" (Rhode, 1929), after making other maneuvers. On landing he was found to have generalized conjunctivitis of both eyes and "generalized systemic neurological symptoms" (not otherwise identified) leading the doctor to "believe that he had a mild cerebral concussion with some generalized cerebral capillary hemorrhage or at least a marked degree of passive traumatic enlargement" due to the centrifugal force. The pilot came back to duty in two weeks, with complete recovery in about a month. In the light of present centrifuge experience, we suspect that the conjunctivitis occurred during a $-G_z$ maneuver, rather than on the pull-up. Rhode notes "....for pursuit airplanes, at least, it is quite possible to break the airplane in the air unless the load factor is made unduly high or the control limited to prevent abrupt maneuvers. Performance in its broad sense is reduced by both of these expediences. If, however, the physical resistance of the pilot is the limiting factor there is no need to curtail performance

by overstrengthening the airplane structure or by reducing the control." Rhode however does not note the delay of three seconds or so for circulatory effects on consciousness to develop, but within which time structural failures may occur. The concept of using the pilot as a "safety valve," counting on his going unconscious before he harms the aircraft, is a hazardous one.

Naylor (1932), after reviewing acceleration effects, stated, "I have not heard that any acceleration experienced in an aeroplane has warranted the adoption of belts by aerobatic pilots." However, Marshall (1933) suggested a pilot belt bracing the entire abdomen to prevent "anaemia of the eyes," to be filled by opening an air scoop when acceleration deflects a weighted valve. Orlebar (1933), who set the world speed record of 368 mph in a Supermarine seaplane in 1929 (Dowd, 1931), felt that an abdominal belt was not needed in racing, but might be in aerobatics. He describes holding a maneuver giving complete loss of vision for 20 seconds, spiralling down 2 1/2 turns, while maintaining control feel and without unconsciousness. He reports that the elastic abdominal belt made by Flack in 1929 was unpopular with pilots. During the war Flack had stressed the importance of abdominal tone. Thus Flack and Bowdler (1918) state, "A soft 'doughy' abdominal wall, with a splashing stomach, in addition to denoting lack of tone by allowing the abdominal pressure to fall, aggravates any tendency to splanchnic flooding. .....one of the first signs of flying stress is to be found in the loss of tone of the abdominal muscles." Orlebar (1933) also comments that some pilots found benefit in tightening up belly muscles in doing the turns as long as they avoided holding their breaths, which reduced venous return and gave loss of vision more quickly. MacWilliam (1935) suggests binding the legs or keeping them in motion to reduce blood pooling there.

We shall terminate here this review of early acceleration studies which has emphasized reports inadequately noted in aviation medicine textbooks. For a further review, see Ham (1942), and particularly Fulton (1948). Jongbloed and Noyens (1932) rekindled interest in animal centrifugation experiments. Von Diringshofen carried flight studies over onto the German centrifuge, built in 1934 (Gauer, 1950). A United States centrifuge was built at Wright Field in about 1935 (Armstrong and Heim, 1938). We note Wood, et al. (1946) saying that the calculations on the launching of the German V-1 indicate "an average force of about 20 g must be developed for a period of about 0.5 seconds. A force of this magnitude would certainly be a hazard if human beings were ever to travel on such missiles."

III. Some Flight and Flight Acceleration Landmarks

(It is recognized that this tabulation is far from complete)

1500: Leonardo da Vinci designed a pyramidal parachute and aircraft whose wings would be flapped by human leg pumping. (Encyc. Brit. 1:245, 1958)

1783, Sept. 19: Jacques and Joseph Montgolfier launched a hot-air balloon with the first vertebrate passengers: a sheep, a duck, and a rooster, making an 8 min. flight to 1, 500 ft. The rooster's wing was broken from a kick by the sheep. The flight was observed by Louis XVI who offered to send up a criminal. (Encyc. Brit. 2: 1007, 1958)

1783, Nov. 21: Pilâtre de Rozier, the king's historian, and the Marquis d'Arlandes made the first human ascent in a Montgolfier hot-air balloon, 45 ft. in diameter and 75 ft. high, 500 ft. up for 25 minutes over Paris, travelling 9 km. (Stewart, 1958)

1783, Dec. 1: J. A. C. Charles, after the first human ascent in a 26-ft. diameter hydrogen balloon with Robert, asked Robert to climb out and abruptly flew alone to 9, 000 ft. before venting sufficient gas to descend. He never flew again. (Encyc. Brit. 2: 107, 1958)

1784: The Robert brothers built the first elongated balloon dirigible, 52 ft. long and 32 ft. in diameter propelled by silk hand-powered oars and steered by a silk rudder.

1784, Nov. 30: John Jeffries and J. Blanchard, in a hydrogen balloon, rose to nearly 9, 000 ft. over England, and there "drank a few glasses of wine to the health of our friends below us." (Jeffries, 1786)

1785, Jan. 7: John Jeffries and J. Blanchard made the first human crossing of the English Channel. (Jeffries, 1786)

1785, June 15: DeRozier and P. A. Romain were killed when their hydrogen and hot-air balloon exploded in attempting to cross the English Channel. They were the first human fatalities in a balloon accident. (Encyc. Brit. 2: 1007, 1958; Stewart, 1958)

1793: Blanchard made the first parachute descent from a balloon (unobserved) breaking his leg. (Encyc. Brit. 17: 251, 1958)

1796: George Cayley (England) designed a helicopter, including wing camber and a movable tail (rudder) for yaw control. He also flew model gliders. In 1809-1810 he explained the stability advantage with wings of an airplane at a dihedral angle. (Zahm, 1912) In urging flight he spoke of the advantages of voyaging in the "ocean which comes to every man's door." (Stewart, 1958)

1797, Oct. 22: Garnerin made the first public parachute descent, of more than 2,000 ft. from a balloon. On Sept. 21, 1802, he parachuted from about 8,000 ft. (Encyc. Brit. 17: 251, 1958)

1803: Robertson, at Hamburg, reached 21,510 ft. in a balloon. (Hamel and Turner, 1914)

1804, Aug. 24: Gay-Lussac and Biot ascended to 13,000 ft.

1804, Sept. 16: Gay-Lussac alone reached 23,000 ft., finding the same gases as on the ground. The air temperature dropped from 82°F to 14.9°F at the peak. (Encyc. Brit. 2: 1008, 1958)

1838, Oct. 3: Hampton made a parachute descent from a balloon, in England. (Jokl, 1942)

1842: William Henson (England) designed and patented a 150-ft. wing span monoplane aircraft with horizontal and vertical rudders to be operated by the pilot. It had twin propellers and a three-wheel loading gear. (Zahm, 1912) Henson and Stringfellow, in 1842, formed the Aerial Transit Company, a bit prematurely. (Rolfe and Dawydoff, 1954)

1848: John Stringfellow's steam-powered airplane model weighing 6.5 lbs. made the first successful powered airplane flight, of 40 yards, after launching from a stretched wire (Zahm, 1912). More recently, it has been questioned that this model actually attained free stable flight. (Stewart, 1958)

1852, Sept. 24: Henri Giffard attained 6.5 mph in a pointed balloon 144 feet long with steam engine and propeller power with rudder control. In later years he patented a design of a balloon 2,000 ft. long which was to attain 44 mph. (Zahm, 1912)

1857: Jean-Marie LaBris very briefly flew in a glider towed by a team of horses. (Rolfe and Dawydoff, 1954)

1859: John Wise travelled by free balloon from St. Louis, Mo., to Henderson, N.Y. (1,120 miles). (Encyc. Brit. 2: 1007, 1958)

1860: Francis Wenham patented the biplane or multi-plane aircraft concept. (Rolfe and Dawydoff, 1954)

1862, Sept. 5: Glaisher went unconscious at 29,000 ft., with the balloon still climbing--descended and survived. (Encyc. Brit. 2: 1008, 1958)

1865: Jules Verne, in De Le Terre á la Lune, proposes that the moon projectile be equipped with "water buffers" to enable the three passengers to survive the shock of firing.

1868: Matthew Boulton designed the three-torque system of aircraft control, with horizontal and vertical rudders and a pair of reverse turning ailerons. (Zahm, 1912)

1868: Stringfellow flew a triplane model with twin propellers and a steam engine, using for the first time the "Pratt truss" arrangement of vertical posts and oblique tie wires to support the wings. (Zahm, 1912) This model did not attain free flight, but was supported on a wire. (Stewart, 1958)

1871, Aug. 18: Alphonse Penoud flew an elastic band-powered model airplane with wings at a dihedral angle and with horizontal and vertical tail surfaces. Stewart, 1958, calls this the first free and stable flight of a powered model airplane.

1872: Haenlein in a coal-gas balloon 164 ft. long driven by a gas engine and propeller using gas from the balloon, attained 10 mph.

1875, Apr. 15: Tissandier, Crocé-Spinelli, and Sivel reached 27,950 ft. in a balloon, using oxygen for the first time. Crocé-Spinelli and Sivel died. (Encyc. Brit. 2: 1008, 1958)

1883: The Mozhaisky airplane flew. (Strizhevsky, 1957) It was piloted by I.N. Golubev, flying 20 to 30 m. (Stewart, 1958)

1883, Oct. 8: The Tissandier brothers, with an electric motor and propeller-powered balloon, attained 8.9 mph.

1884, August 9: The 165-ft.-long hydrogen balloon "LaFrance" under the command of Renard and Krebs, flew the first balloon closed course. It made 7 flights in all, 5 in closed courses. It had a buoyancy of 4,400 lbs. It had batteries and an electric motor. (Zahm, 1894)

1884: Horatio Phillips patented a wing profile like that of modern airplanes, after wind tunnel tests. (Zahm, 1912) By 1893 his model, weighing 330 lbs., had flown 2,000 ft. at 40 mph. The wings were like Venetian blinds 8 ft. high and 22 ft. wide, composed of horizontal slats 1.5 inches deep, 22 ft. wide, and two inches apart. (Zahm, 1894)

1890, Oct. 9: Clément Ader, in France, was reported to have flown 164 ft. in a steam-driven wheel-mounted monoplane with twin screws (Zahm, 1912). He flew very briefly again on August 18, 1897, and crashed. This was not considered free and stable powered flight. (Stewart, 1958)

1891-1896: Otto and Gustav Lilienthal demonstrated the superior lift with curved instead of flat wing surfaces, making over 2,000 manned glider flights. Control was achieved by shifting body weight. A tail was not used in early flights. Otto Lilienthal was killed on August 9, 1896 when his glider was upset by a sudden gust of wind. (Encyc. Brit. 14: 122, 1958)

1894, July 31: Hiram Maxim's steam-powered aircraft with 104-ft. wing span, supported 3 men and 10,000 pounds for a flight of 300 ft., restrained between rails. (Maxim, 1908)

1894, Dec. 4: A. Berson reached 31,500 ft. in a balloon from Strassfurt, recording a temperature of -54°. (Encyc. Brit. 2:1008, 1958)

1895, Sept. 12: Percy Pilcher (England) made his first manned glider flights, with a glider having a vertical tail. A later model had wheels for landing. He was killed in a glider accident in 1899. (Stewart, 1958)

1896, May 6: Samuel Langley's steam-driven model aircraft flew 1,500 yards. (Anon., 1918)

1896, June-Sept.: Octave Chanute carried out manned glider experiments, leading to the development of the cross-braced and trussed biplane, with elastically flexible control surfaces to increase stability and ease manual control by body displacement. (Zahm, 1911a)

1897, July 11: Andrée, Fraenkel, and Strindberg attempted to balloon over the North Pole from Spitsbergen. They came down 500 miles from the Pole and perished, being discovered in 1930. (Encyc. Brit. 2: 1007, 1958)

1897: David Schwarz attempted to fly the first rigid airship, using a gasoline engine. It had an aluminum frame and sheathing. (Encyc. Brit. 1: 463, 1958)

1898: Santos-Dumont drove an 82-ft.-long non-rigid dirigible with a gasoline motor cycle engine. (Zahm, 1912)

1900: Henry de la Vaulx travelled from Paris to Korostyshev in a free balloon (1,183 miles). (Encyc. Brit. 2: 1007, 1958)

1900, July 2: Zeppelin launched his first rigid dirigible (the first of about 100), 416 feet long, weighing 9 tons and displacing 10 tons, driven by two petrol engines to 17.4 mph. (Zahm, 1912)

1901: Berson and Süring reached about 35,600 ft. over Berlin in a hydrogen balloon, going unconscious even on 100 per cent oxygen. (Encyc. Brit. 2: 1008, 1958)

1903: A. P. Thurston was thrown to the floor and went unconscious at 6.4 G in a Maxim "twin-about" flying machine restrained by radial wires. Thurston may have been the first human to become unconscious under acceleration. (Thurston, 1952)

1903, Aug. 8: A one-quarter scale model of Langley's "aerodrome" airplane flew successfully, the first successful gasoline motor-powered airplane flight.

1903, Sept. 7: Charles Manly, at the controls of the full-size Langley "aerodrome" airplane, crashed on catapulting from the roof of a houseboat. (Zahm, 1912) A second launching attempt also failed. This same aircraft, with pontoons and a different motor, was flown successfully by Curtis in 1914. (Zahm, 1914)

1903, Dec. 17: Orville and Wilbur Wright made four successful flights with a gasoline-powered biplane, the longest of which was 59 seconds, the first successful stable manned powered unrestrained airplane flight. The average flying speed was 31 mph. (Stewart, 1958)

1904, Sept. 15: Orville Wright made the first turns in manned powered airplane flight. (Zahm, 1912)

1904, Sept. 24: Orville Wright made the first full circle in manned powered airplane flight. (Zahm, 1912)

1904, Oct. 4: A Wright airplane flew for 30 minutes.

1905, April: Montgomery demonstrated control of a manned glider by means of horizontal and vertical rudders and reverse-turning torsional control wings. (Zahm, 1912)

1906, Nov. 12: A. Santos-Dumont made the first public manned powered airplane flight, 21.2 seconds duration. (Loening, 1910) He flew 190 m. at a height of 3 m. (Stewart, 1958).

1908, Jan. 13: The first flight was made in the Henri Farman biplane. (Loening, 1910) This had rudder pedals operated by the feet and a right-hand control lever with aft motion for pitch up, and right motion for roll right (operating a pair of counter-rotating "wing tips").

1908: Ellhamer made the first flight of the Aerial Experiment Association airplane at Hammondsport, N. Y., with the first practical use of the aileron system. (Zahm, 1912; Wild, 1931)

1908: Breguet made a flight in a helicopter rising 4 to 5 m. and traveling 20 m. (Stewart, 1958)

1908: Alliott V. Roe and Robert Esnault-Pelterie are considered originators of the roll and pitch control column. (Stewart, 1958)

1908, Sept. 17: Lt. Thomas Selfridge was killed in a crash when a propeller broke on a Wright aircraft, the first fatal powered airplane accident. Orville Wright was severely injured.

1908: Wilbur Wright gave his first flying exhibitions in Europe, ascending only when smoke from his cigarette went straight up, and then only on dull days or in the morning or toward dusk. (Hamel and Turner, 1914)

1908, Dec. 31: Orville Wright made a flight lasting 2 hours and 20 minutes.

1909, July 19: Hubert Latham, trying to cross the English Channel before Blériot, had engine trouble six miles out. As a French destroyer rushed up to rescue him from the sinking Antoinette monoplane, Latham, coolly lit a cigarette, a later tradition for pilots who "broke wood" uninjured. (Stewart, 1958)

1909, July 25: Louis Blériot made the first airplane flight across the English Channel in 35 minutes, from Calais to Dover, in his 7.8 m.-wing span monoplane. Enroute on a cloudy day, he was out of sight of land for 10 minutes but fortunately (without compass) by touching nothing, and letting his "hands and feet rest lightly on the levers" he maintained a sufficiently straight course to sight Dover. He was greeted among others by a British Customs official who asked him to declare his goods. (Stewart, 1958)

1909: Glenn Curtiss beat Blériot in the first Gordon-Bennett cup race at Rheims, France, with an average speed of 43 mph. (Wild, 1931)

1909, Oct. 22: Hubert Latham, at Blackpool in an Antoinette monoplane, demonstrated flying in high winds, 90 mph downwind, and occasionally backwards upwind. (Hamel and Turner, 1914)

1910: The Pfitzner monoplane had three degrees of freedom in the control column, with pitch by fore and aft motion, yaw by twisting or yawing the column, and roll by turning the wheel at the top of the column. (Loening, 1910)

1910: Chavez flew across the Alps, crashing fatally on landing, perhaps because of frost-bitten limbs. (Hamel and Turner, 1914)

1910: The "vol plané", a power-off dive and landing, was developed, then the spiral dive. (Hamel and Turner, 1914)

1910: The pilot of the Wright aircraft at the Nice race of 1910 first used lateral control to intentionally bank on corners. Efimoff, piloting a Farman biplane, then tried this and by the end of the race, most of the pilots had mastered this new flight technique. (Hamel and Turner, 1914)

1911: Zahm suggested an accelerometer design, and tested the factors of safety of wings by static loading and a wire tensiometer.

1911: Schütte and Lanz built a 430-ft. rigid dirigible (the first of 22) and attained 50 mph.

1911, April: H. J. D. Astley was thrown out of his seat when he switched on the engine in a dive. He caught the wires, crawled back into his seat and recovered control. (Hamel and Turner, 1914)

1911, August: Capt. H. R. Reynolds's Bristol biplane was turned over by the wind, throwing him onto the underside of the upper wing. The aircraft remained inverted, sideslipping to the ground. Reynolds survived. (Hamel and Turner, 1914)

1911: C. P. Rodgers and Fowler were the first to fly an airplane across the United States from New York to Pasadena, taking 59 days and repeatedly rebuilding the airplane. (Manly, 1942)

1911, Sept. 4: Roland Garros, in a Blériot monoplane, set a new world's airplane altitude record of 3,910 meters (12,828 feet). (Zahm, 1912)

1911, Sept. 7: A Curtis hydroplane was launched by sliding down a wire. (Zahm, 1911b)

1911, Sept: Gustav Hamel flew the first air mail from Hendon to Windsor. (Stewart, 1958)

1911, Dec. 31: John Moisant was killed when he was thrown from his aircraft when abruptly steepening a dive, without lapbelt, possibly due to "gyroscopic" forces. (Anon., 1911)

1912, March 1: J. Védrines, in a Deperdussin monoplane, set a new world's speed record of 166.8 km/hr (103.8 mph).

1912, June: Garros and Hamel made the first spiral or corkscrew descents in monoplanes, turning in a diameter no more than twice the machine's length. This maneuver was first done by American pilots in Wright biplanes. (Hamel and Turner, 1914)

1912: Wilfred Parke, in a spiral dive, was thrown outboard, but caught the wires and landed safely. (Hamel and Turner, 1914; also Flight, Aug. 31, 1912)

1912: Capt. Berry made the first descent by parachute from a moving aircraft at St. Louis. (Anon. 1912)

1912, Sept.: Georges Fourny set the aircraft flight-duration record of 13 hours, 17 minutes. (Hamel and Turner, 1914)

1913: Prévost, in the Gordon-Bennett race, at 126 mph, was distressed at the labor of keeping his machine steady through the heat eddies that day. (Hamel and Turner, 1914)

1913: The British Royal Flying Corps was established, with the motto, "Per Ardua ad Astra." (Hamel and Turner, 1914)

1913: Capt. Aubry's Deperdussin monoplane was blown by a gust of wind onto its back. The pilot, who was strapped in, recovered normal attitude and control.

1913, Aug. 19: Adolphe Pégoud made a parachute jump from an aircraft in flight. (Anon., 1913). As he descended he saw his abandoned airplane do a number of maneuvers, including inverted flight. (Stewart, 1958)

1913, Sept. 1: Adolphe Pégoud, after modifying a Blériot monoplane by strengthening the wings and adding a larger tail, and after training at the controls with the aircraft upside down on trestles, made the first intentional upside-down flight. The motor was turned off while inverted. He wore shoulder straps with the lap belt. He later flew loops and outward somersaults, and turned over sideways in the air. (Anon., 1913; Hamel and Turner, 1914). Pégoud was killed in aerial combat on Aug. 31, 1915. As Védrines said, "He taught the world how to fly" with his demonstrations of the maneuverability of aircraft. (Stewart, 1958)

1913: Igor Sikorsky built a four-engine airplane, the "Grand", with glass-enclosed cabin, which flew with 11 men. (Stewart, 1958)

1913: P. N. Nesterov (evidently shortly before Pégoud), intentionally flew loops near Kiev. (Ostoslavskiy, 1957)

1913, Sept. 23: Roland Garros flew across the Mediterranean Sea (500 miles) from Cannes to Bizerta. (Hamel and Turner, 1914; Stewart, 1958)

1913: Pégoud, for Blériot, took off and landed on a cable. (Hamel and Turner, 1914; Stewart, 1958). (The cable was invented by Levavasseur.)

1913, Oct. 15: The first regular air mail commenced, from Paris to Bordeaux. (Hamel and Turner, 1914) In 1912 mail was carried in special events in India, and on Long Island, N.Y. and other U.S. cities.

1913, Dec. 27: Legagneux set the airplane altitude record of 6,150 meters (20,180 ft.) using oxygen. (Hamel and Turner, 1914)

1917: Searle built and flew with a recording accelerometer, showing 4.2 G in "dog fight" maneuvers.

1918: Maj. V. H. reported that "the sky appeared to be so grey", and he fainted, while doing a "tight" turn at 4.6 G. (Head, 1919)

1918: The Zeppelin dirigibles had attained a payload of 50 tons, a speed of 80 mph, and a ceiling of over 20,000 ft. (Encyc. Brit. 1: 464, 1958)

1919, May 6-31: Albert Read, Walter Hinton, and Stone flew the Curtiss NC-4 from Long Island to Plymouth, England (4,532 miles), stopping at Newfoundland, the Azores and Lisbon. (Stewart, 1958)

1919, June 14-15: John Alcock and Arthur Brown flew a Vickers Vimy bomber from St. Johns, Newfoundland, to Ireland (1,936 miles) in 16 hours and 12 minutes. Enroute, turbulence sent them into a spin from which they barely recovered, with ocean spray in their faces. Brown had to climb on the wings to pick away ice from the engine air intakes, inches from the propeller. (Stewart, 1958)

1919, July 2-4: The British rigid airship R-34, under the command of G. H. Scott, flew from Scotland to New York in 108 hours. The return trip, July 9-11, took 75 hours. (Stewart, 1958)

1919, Nov. 12-Dec. 10: Ross Smith, Keith Smith, J. M. Bennett, and W. H. Spiers flew a Vickers Vimy Bomber from England to Australia via India. (Stewart, 1958)

1920: R. W. Schroeder set the airplane altitude record of 31,115 ft., using a supercharger. (Rolfe and Dawydoff, 1954)

1921: Fronval, the French pilot, set a record for looping, with 962 loops in 3 hours 52 minutes, 10 seconds, with an average angular velocity of 25°/sec., without giddiness. (Wulfften-Palthe, 1922)

1921: Norton and Allen built an improved linear accelerometer.

1921, June 8: A pressure cabin was installed in a United States airplane, but the pressure was inadequately controlled from a supercharger. (Armstrong, 1939)

1922: Reid built an angular accelerometer and an instrument to measure the three orthogonal linear accelerations in flight. (Reid, 1922)

1922: James Doolittle flew from Jacksonville to San Diego in 22 hours.

1922: Lt. K. L. Maughan in the Pulitzer race reported going unconscious on the turns. (Bauer, 1926)

1923, Jan. 9: A. Gomez Spencer first flew the Autogiro, designed by Don Juan de la Cierva. (Stewart, 1958)

1923, February: McReady and Kelly made the first non-stop U.S. transcontinental airplane flight. (Rolfe and Dawydoff, 1924)

1923: Lt. "Al" Williams, winner of the Pulitzer race, at a speed of 243.7 mph, said that in a practice flight he passed out completely on a turn. (Dowd, 1931)

1924, April 6-Sept. 28: Lowell Smith and Eric Nelson, in two Douglas DWC-1 biplanes, flew around the world in 175 days. (Rolfe and Dawydoff, 1954; Stewart, 1958)

1924: James Doolittle described maneuvers at 7.8 G carried out very abruptly without trouble, but at 4.5 G for a few seconds producing loss of vision.

1924-1932: The 658-foot long dirigible "Los Angeles" made 331 flights before decommissioning, including the hooking-on and releasing of airplanes in flight. (Encyc. Brit. 1: 466, 1958)

1925: A party led by Roald Amundsen, in two Dornier seaplanes, flew within 220 km. of the North Pole. On a stop, one of the seaplanes was frozen into the ice, but all the crew returned safely in the other. (Stewart, 1958)

1927: Hawthorne Gray reached 42, 470 ft. in an open gondola balloon, but died before descent. (Encyc. Brit. 2: 1008, 1958)

1927, May 20-21: Charles Lindbergh made the first solo flight across the Atlantic, New York to Paris, 5, 820 km. (3, 610 miles) in 33 1/2 hours. Nungesser and Coli had started across the Atlantic from Paris on May 8, but were never heard of again. (Stewart, 1958)

1927, Oct.: Costes and Le Brix were the first to fly an airplane across the South Atlantic. (Stewart, 1958)

1927: Luke Christopher made abrupt airplane pull-ups, reaching 10.5 G. (Rhode, 1929)

1928, Mar. 15: Volckhart drove the first rocket car, on railroad tracks, in cooperation with von Opel and Valier.

1928, July 11: F. W. Sander achieved the first rocket airplane flight, a distance of 4, 000 ft. in 70 sec. (Haley, 1958) (Stewart, 1958 reports this as F. Stamer flying a glider powered by a rocket on June 11, 1928.)

1929: Hugo Eckener commanded the "Graf Zeppelin" dirigible in a 21, 700 mile around-the-world flight, in 20 days and 4 hours. (Encyc. Brit. 1: 464, 1958)

1929, Sept. 30: Fritz von Opel made a successful rocket airplane flight of 2 km. (Stewart, 1958)

1929: The Dornier DO-X twelve-engine seaplane, with 157-foot wing span, carried 169 passengers. (Rolfe and Dawydoff, 1954)

1931, June 23: Wiley Post and Harold Gatty made an airplane trip around the world (15, 500 miles) in 8 days, 15 hours, 51 minutes. Post substituted a "largish armchair" for the pilot's bucket seat. (Stewart, 1958)

1931, Sept. 13: John Boothman won the last Schneider Trophy race in a Supermarine S6B seaplane, designed by R. E. Mitchell, at 548 km. /h., an official speed record. (Stewart, 1958)

1931: George Stainforth flew the Supermarine S6B at 657 km./h., an official speed record. (Stewart, 1958)

1931, Nov.: Bert Hinkler made the first solo flight across the South Atlantic, West to East. (Stewart, 1958)

1931: Auguste Piccard and Paul Kipler reached 51, 793 ft. in a closed gondola balloon. (Encyc. Brit. 2: 1008, 1958)

1932: Auguste Piccard and Max Cosyns reached 55, 577 ft. in a closed gondola balloon. (ibid.)

1933: C. L. Fordney and T.G.W. Settle reached 61, 237 ft. in a closed gondola balloon. (ibid.)

1934: Renato Donati reached 37, 352 ft. in an airplane, wearing a full pressure suit. (Gell, et al., 1959)

1935: The large German centrifuge was built at the Sanitäts-Versuchsstelle der Luftwaffe.

1935, Aug. 5: Marcel Cogno reached 32, 800 ft. in a pressurized cabin airplane. He crashed, with indications of decompression the cause. (Armstrong, 1939)

1935: A light-weight centrifuge was built at Wright Field.

1935, Nov. 11: Albert Stevens and Orvil Anderson reached 22, 066 m. (72, 395 ft.) in a pressurized gondola balloon. (Encyc. Brit. 2: 1008, 1958; Armstrong, 1939)

1936, Sept. 28: Swain, in one of the first full pressure suits, at 2.5 psi, reached 15, 230 m. (49, 944 ft.) in an airplane. (Armstrong, 1939)

1937, April: The pressurized cabin airplane XC-35 (Lockheed) was flown. (Armstrong, 1939)

1937, June: Chkalov, Baidukov, and Belyahov made the first non-stop airplane flight across the North Pole. (Stewart, 1958)

1937, June 6: Adam, in a full pressure suit, set the airplane altitude record of 59, 937 ft. (Armstrong, 1939)

1938, July 10-14: Howard Hughes and a crew of four flew around the world (14, 791 miles) in 3 days, 19 hours, and 8 minutes. (Encyc. Brit. 2: 810B, 1958)

1939, Aug. 27: Warsitz made the first flight of the Heinkel 178 jet airplane, the world's first flying jet. (Stewart, 1958)

1939: Warsitz flew the rocket-propelled Heinkel 176. (Stewart, 1958)

1940, Aug. 27: The Caproni-Campini jet airplane made its first flight. (Stewart, 1958)

1941: The Toronto centrifuge was put into operation.

1941, May 15: P. E. G. Sayer made the first flights of the first British turbojet airplane, the Gloster 28/39. (Stewart, 1958)

1942: The Mayo Clinic centrifuge was put into operation.

1943: The present centrifuge was put into operation at Wright Field.

1943: Cass Hough exceeded 780 mph in dives from 43, 000 ft. in a P-38 and in a P-47. (Zim, 1943)

1943: A human centrifuge was built in Australia.

1944, 1945: The Germans operated the Me-163 (speed 560 mph) and the Natter manned rocket airplanes. (Haley, 1958) The Julia rocket airplane was also flown.

1944, July 5: The piloted MX-324 rocket airplane interceptor made by Northrup made its first flight. (Haley, 1958)

1944: The Germans flew the first jet fighter in combat, the Me-262. The Gloster "Meteor" did not see combat. (Rolfe and Dawydoff, 1954)

1945: The Pensacola human centrifuge was put into operation.

1947, Aug. 29: Films were made of a human ejecting from a Gloster "Meteor" at 505 mph. (Bergin, 1949)

1947, Oct. 17: Charles Yeager, in the X-1 rocket research airplane, made the first level flight at a speed above Mach 1. (Encyc. Brit. 2: 810B, 1958), reaching 1, 558 km. /h. (968 mph). (Stewart, 1958)

1951: The Johnsville human centrifuge was put into operation.

1951, Aug. 15: William Bridgeman, in the D-588-II rocket airplane, reached 1, 238 mph (an unofficial speed record because the FAA rules of ground takeoff were not followed) with lateral oscillations of up to 75°. In another flight he reached 79, 494 ft. to be the first in an airplane to take the human altitude record from the balloonists. (Rolfe and Dawydoff, 1954)

1953, Aug. 31: Marion Carl, in the D-558-II, reached 83, 235 ft. (Coombs, 1954)

1953: "Skip" Ziegler was killed on crashing during an early flight of the first X-2, following a fuel-system explosion before launch. (Gubitz, 1960)

1953, Nov. 20: Scott Crossfield, in the D-558-II, reached 1, 328 mph, the first man to exceed Mach 2. On Oct. 14 he had reached 1, 272 mph, after over 50 flights in the D-558-II. (Coombs, 1954)

1953, Dec. 12: Charles Yeager, in the X-1A, reached 1, 635 mph (Mach 2.5), at 76, 000 ft., experiencing severe lateral oscillations due to the limited aerodynamic control at this altitude.

1953: Walter Gibb, in an English Electric Canberra, set an official aeroplane altitude record of 19, 406 m. (63, 668 ft.). (Stewart, 1958)

1954, Aug. 3: R. T. Shephard flew the "flying bedstead" designed by Dr. A. A. Griffith, in the first free flight, to an altitude of 40 to 50 m. This has two jet motors pointed downward on a frame supporting the pilot, with bleed air jets for stability control. (Stewart, 1958)

1954, Aug. 21: Arthur "Kit" Murray flew the X-1A to over 90, 000 ft.

1955: R. R. Scott flew across the United States in 3 hours, 44 minutes.

1956, July 23: Frank "Pete" Everest flew the second X-2 rocket airplane to 1, 900 mph.

1956, Sept. 7: Iven Kincheloe flew the X-2 to 126, 000 ft.

1956, Sept. 27: Milburn Apt reached 2, 078 mph (Mach 3.3) in the X-2. Severe oscillations caused him to eject; he was killed.

1956, Nov. 8: Malcolm D. Ross and M. Lee Lewis reached 76, 000 ft. in a closed gondola balloon. (Encyc. Brit. 2: 1008, 1958)

1957, Jan. 16-17: Old commanded a B-52, around the world (24, 325 miles) in 45 hours, 19 minutes. (Encyc. Brit. 2: 810B, 1958)

1957, July 16: John Glenn flew an F8U from Los Angeles to New York in 3 hours, 23 minutes.

1957, Aug. 19-20: David Simons reached 102, 000 ft. in a closed gondola balloon, the Manhigh II. (Simons, 1958, 1959)

1957, Oct. 3: Sputnik 1 went into orbit.

1957, Oct. 18: Malcolm Ross and M. L. Lewis reached 86, 000 ft. in a closed gondola balloon, Strato-Lab High #2, the altitude record for two men. (Ross, 1959; Foster, 1961)

1957, Nov. 3: Sputnik 2 carried the first animal into orbit, the dog Laika.

1959, June 8: Scott Crossfield made the first free flight, unpowered, of the X-15.

1959, Dec. 12: Joseph Rogers set an official speed record over a straight course of 1, 526 mph in an F-106A jet airplane.

1959, Dec. 14: Joe Jordan reached 103, 395 ft. in an F-104C jet aircraft, under official altitude record conditions.

1960, Aug. 4: Joseph Walker reached 2, 196 mph in the X-15, still with the small XLR-11 engines.

1960, Aug. 12: Robert White reached 136, 500 ft. in the X-15, still with the small XLR-11 engines.

1960, Aug. 16: Joseph Kittinger reached 102, 800 ft. in an open gondola balloon, followed by bail-out and a 17-mile free fall before opening the main parachute.

1960, Sept. 25: Cdr. John Davis flew the F4H-1 Phantom II, U.S. Navy fighter at an average course speed of 1390.2 mph over a 100 km. closed course, under official speed record conditions. The actual average flight speed, for the slightly longer path taken, was 1,454 mph.

1961, March 7: Robert White flew the X-15 with the XLR-99 large engine to 2,905 mph.

We conclude this table with a quotation from Stewart, 1958:

"Speed, originally seen as a useless 'craze', is now seen as the key to man's liberation from his gravitational cage. The pattern of the future has been outlined in unmistakable terms by Esnault-Pelterie, in 1907, by Goddard in 1919, and by Oberth in 1923. The attainment of greater heights is teaching us how man may be protected in the remoter places which he will one day assuredly visit. It has all arisen out of aviation and, although it will be no longer aviation in the exact sense, for it will be a form of direct reaction movement instead, it will still owe its existence to aviation and to those inventors, pioneers and designers who made aviation the fastest developing form of human endeavor yet known."

IV. The Use of G or g

Table I indicates the varying means used to express the resultant acceleration. We have not yet succeeded in tracing the origin of normalizing the resultant acceleration in terms of the acceleration of gravity. Galileo evidently knew that a mass on a table falling with hindrance had a resultant acceleration (as measured by its weight) equal to the acceleration of gravity minus the acceleration of the table. After Airy's use (1856) of the symbol G for an acceleration of gravity, this symbol, instead of g, apparently was introduced by chance into the acceleration literature, appearing in the figures of Norton and Allen's work (1921), but not in the text. However, Zahm (1893) used G for the force of gravity. It has had a sporadic use since (Table I). Dixon and Patterson attacked the use of g, wanting it reserved for the acceleration of gravity alone, but their use of G can also be attacked for its general use for the gravitational constant. The symbol, g, is also used for the gram (Forsythe, 1954).

Searle and Cullimore (1918) emphasize the importance for computing aircraft position of being able to separate displacement accelerations from the resultant acceleration, as measured by accelerometers by measuring aircraft attitudes as well as

accelerations, and removing the effects of gravity. The aerodynamicist is concerned with the position of the aircraft above the earth; his terminology emphasizes displacement accelerations, and weight due to gravitation enters separately into his equations. An aircraft in straight flight at constant speed has no displacement acceleration; $a = o$. But weight due to gravitation continues to act, in a direction which can be specified by the aircraft attitude angles. The biologist is not concerned with this distinction between displacement and gravitational accelerations. He needs a terminology that gives the combined effects of both factors, as measured by displacements of the inertial masses of accelerometers or by displacements within the body. In straight and level flight at constant speed, the heart is pulled down within the chest by gravitation; the biologist, and the pilot, would say that the crew is at 1 G, although indeed the displacement acceleration is zero. From long convention, one speaks of "positive G" when the heart is displaced downward.

The aeronautical engineer has an alternate terminology to emphasize the "load" or "resultant acceleration" aspect, rather than the displacement aspect. Thus in straight and level flight at constant speed, he speaks of a "normal load" of 1 g (which we now suggest he call 1 G to emphasize that it is a resultant acceleration with both displacement and gravitation components), and he designates this as n_z, positive in straight and level flight or in an inside loop, to distinguish it from the displacement acceleration a_z, which is positive when the aircraft does an outside loop.

It is appropriate then that the biologist standardize on an acceleration terminology which applies to the crew member whatever his position and attitude in or out of the vehicle, that this terminology be distinguishable from the vehicle displacement acceleration terminology so that there will not be confusion as to which system is being used, that the biological terminology relate to the combined effect of gravitational and displacement accelerations, and that the terminology of acceleration components is mathematical rather than verbal. Ideally, a proposed biological terminology should bear a simple relation to present usage to simplify its adoption.

These terminology problems were recognized, and an organized solution was presented by Dixon and Patterson (1953). Their proposals, however, have not been widely adopted. They recommend that G be the symbol of acceleration, reserving g_o for the gravitational constant at sea level and g for the gravitational constant at any altitude. They use G, however, for the mathematical symbol for both magnitude and direction of acceleration,

TABLE I

Various Means of Describing an Acceleration of 2 G_z

2.0 der gravitations beschleunigung	Breuer and Kreidl 1898
C = 2	von Wuensch 1898
2 gravitational units, 2 times the weight	Zahm 1911c
2 times the weight	Zahm 1913
2 g	Hunsaker and Wilson 1915
2 g	Searle and Linderman 1917
2 g, 2 times the weight	Searle and Cullimore 1918
2 g	Head 1919
2 g	Zahm 1919
2 fois la pesanteur	Broca and Garsaux 1919
2 "g"	Davies 1920
2 g, 2 "g"	Bairstow 1920
2 g. (text), 2 G. (figures)	Norton and Allen 1921
2 'g', 2 g.	Doolittle 1925
g x 2, 2 g	Framme 1931
2 g	von Diringshofen and Belonoschkin 1932
2 g	Jongbloed and Noyens 1932
2 g.	Naylor 1932
2 G.	Marshall 1933
g x 2	Schubert 1935
2 g.	Brouwer 1935
2 g	Rook and Dawson 1938
2 G's	Armstrong and Heim 1938
2g	Ruff and Strughold 1939
2 g	Apollonov, Arutjunov, et. al. 1939
2 G's	Armstrong 1939
g = 2, 2g	Livingston 1939
2 g's	Grow and Armstrong 1941
2 g.	Poppen 1942
2 g	Fulton 1942
2 g	Jokl 1942, 1943
2 g.	Ham 1943
2 G's	Bauer 1943
2 G	Stewart 1945
2 "g"	Hall, et. al. 1945
2 g	Wood, et. al. 1946

Table I (Cont)

2 g	Code, Wood and Lambert 1947
2 g	Fulton 1948
2 'g'	Bergin 1949
2 G	Lombard 1951
2 g's	Armstrong, 3rd edition, 1952
2 physiologic G-units;) G* = 2)	Dixon and Patterson 1953
2 g	Stapp 1955

requiring them to say for example, "G equals 5 for the pull-up acceleration," instead of the more common "the pull-up acceleration is 5 G." Table I gives the acceleration symbols used by some other authors. Some authors speak of "G stress" but also write, for example, 5 g. The NACA usage was "5g," although some NASA authors write "5G" (Smedal et. al, 1960). We propose that G be used for the unit vector of acceleration normalized to the gravitational constant g_o, and representing the full reactive load, including both displacement and gravitational aspects. We hope that g will continue to be used for the aircraft displacement acceleration, so that these terminologies will be readily distinguished.

We could then say that in straight and level flight at constant speed, the aircraft has a_z = Og (or is at Og_z), but the pilot experiences 1 G_z. An aircraft looping with a_z = 1 g (or at $1g_z$) would expose the pilot to $2G_z$ at the bottom of the loop and OG_z at the top. Dixon and Patterson (1953) proposed the symbols G for the displacement acceleration and G* for the combined displacement and gravitational accelerations. Since their proposals have not been adopted, the standardization within present usage of g for displacement accelerations, usually specified at the center of gravity of the vehicle, and G for the combined displacement and gravitational accelerations, usually measured at a crew member's position, is recommended. Note that accelerometers measure G, not g, at their positions.

V. Aircraft and Human Axis Systems and Acceleration Terminologies

Table II illustrates the variety of axis systems which have been proposed. Initial emphasis was on the motion of the relative wind, as the aircraft moved through the air; the X axis was positive when this wind moved toward the aircraft tail. The early United States National Advisory Committee for Aeronautics terminology

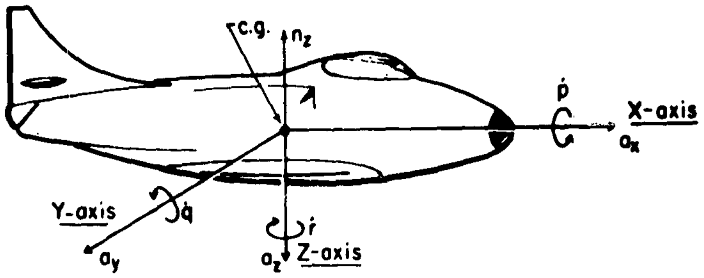
TABLE II

Body Displacement Axes

Vehicle Motion (Clarke and Bondurant)	NASA Aircraft (Body axes)	Early NACA (Wind axes)	Ruff & Strughold, Dixon & Patterson	Byford	Ostos-lavskiy	Galkin
Forward	+x	-x	+x	-z	+x	-y
Backward	-x	+x	-x	+z	-x	+y
Rightward	+y	-y	-y	+x	+z	-x
Leftward	-y	+y	+y	-x	-z	+x
Downward	+z	-z	-z	-y	-y	-z (spine)
Upward	-z	+z	+z	+y	+y	+z

(Hunsaker and Wilson, 1915), following Bairstow and the 1912-1913 Technical Report of the British Advisory Committee for Aeronautics, emphasized such "wind axes," with X positive to the rear, Y positive to the left, and Z positive up. Interestingly, the first NACA report on "Nomenclature for Aeronautics" (Anon., 1916) specified these axes but did not specify sign. Subsequent NACA reports of this same title give the signs, but do not note that "wind axes" are being described. Alternately the aircraft "body axes" may be specified, for displacements over the ground, with X positive forward, Y to the right, and Z downward (Bairstow, 1920). It is this terminology that is now widely used in western aerodynamics texts, and by NASA (Figure VI). Unfortunately, international agreement on this aerodynamics terminology has not yet been reached, and alternate vehicle axes still are proposed. (Table II)

In specifying human acceleration experiences, it would seem reasonable to use the NASA vehicle displacement acceleration terminology. Appropriate transformations (Dixon and Patterson, 1953) could be used to provide the accelerations at the crew stations, taking into account seat back angles and other geometric factors. But this vehicle displacement terminology has these disadvantages: 1) The displacement acceleration does not include the gravitational effect, as discussed above, and this difference may be of importance physiologically. The biologist is concerned with the total reactive load. 2) The sign of the NASA Z axis is such that an inside loop would involve upward or negative displacement of the aircraft, whereas by long medical tradition this is called positive G, based probably on the fact that most aircraft maneuvers involve accelerations between O and $+5G_z$, as indicated indeed in the first paper



NASA AIRPLANE AXIS SYSTEM
(Vehicle Displacement)

Linear Acceleration Modes

Description of Aircraft Motion	Symbol	Unit
Acceleration forward (surge)	$+a_x$	ft/sec² or g
Deceleration (Accelerate backward)	$-a_x$	ft/sec² or g
Downward Acceleration	$+a_z$	ft/sec² or g
Upward Acceleration (heave)	$-a_z$	ft/sec² or g
Straight and level flight at constant speed	$a_z = 0$	
Acceleration to right (sway)	$+a_y$	ft/sec² or g
Acceleration to left	$-a_y$	ft/sec² or g

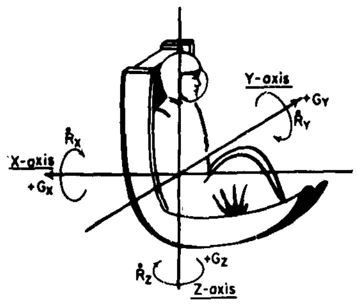
$\underline{a} = \underline{a}_x + \underline{a}_y + \underline{a}_z$

Angular Acceleration Modes

Angular acceleration about X-axis(roll right)	$\dot{p}$	rad/sec²
Angular acceleration about Y-axis(pitch up)	$\dot{q}$	rad/sec²
Angular acceleration about Z-axis(yaw right)	$\dot{r}$	rad/sec²

Figure VI. Description of the vehicle acceleration environment.

recording accelerations in flight. (Searle and Lindeman, 1917)
3) Although the transformations for accelerations at crew stations and with the crew not aligned with the aircraft axes are procedural, the biologist should have as his primary concern the accelerations which produce the biological effects, namely those at the crew stations along the biological axes. Since the NASA axes are well established, the biological axes should correspond to these axes to the extent possible. Byford, and Galkin, have proposed other axes, (Table II). The sign of the biological acceleration along the spinal axis should also conform to the present usage that "heart down" or "eyeballs down" should be positive G. With these restrictions we therefore arrived at the proposed physiological acceleration terminology, Figure VII.



(Directions Are Those of Heart Displacement, With Respect to the Skeleton)

Linear Acceleration Modes

Description of Heart Motion

ACTUAL	OTHER DESCRIPTION		UNIT VECTOR
Towards spine	Eye-balls-in	Chest-to-back	$+G_X$
Towards sternum	Eye-balls-out	Back-to-chest	$-G_X$
Towards feet	Eye-balls-down	Head-to-foot	$+G_Z$
Towards head	Eye-balls-up	Foot-to-head	$-G_Z$
Towards left	Eye-balls-left	——	$+G_Y$
Towards right	Eye-balls-right	——	$-G_Y$

$$NG = \frac{a}{g} = N_1 G_X + N_2 G_Y + N_3 G_Z$$

$$N^2 = N_1^2 + N_2^2 + N_3^2$$

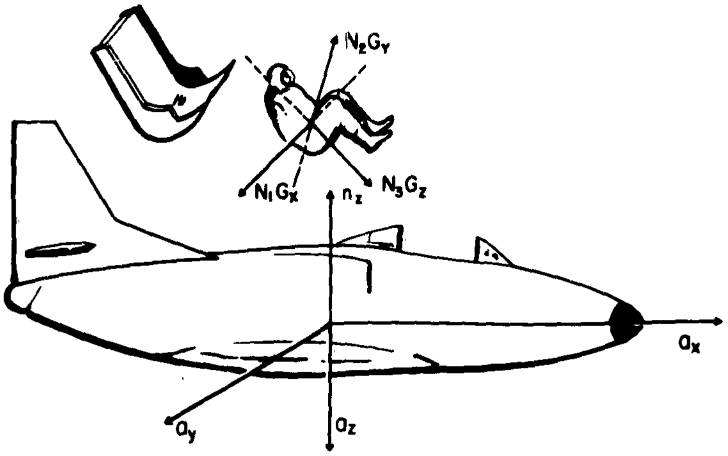
Angular Acceleration Modes

Acceleration about X-axis (The heart rolls left in the chest)	$+\dot{R}_X$
Acceleration about Y-axis (The heart pitches down)	$+\dot{R}_Y$
Acceleration about Z-axis (The heart yaws left)	$+\dot{R}_Z$

Figure VII. Physiological description of acceleration.

This physiological terminology emphasizes body reactions; the positive directions along the axes are directions of reactive displacements. Positive G_z means that the heart is pulled downward, hence the physiological Z axis is positive down the spine. When the aircraft is catapulted at $3g_x$ (displacement acceleration forward), the heart is forced backwards, with the body at 3 G_x; the positive physiological axis is taken as front to back. When the aircraft yaws right at 1 g_y (displacement acceleration to the right), the heart moves to the left, at 1 G_y; the positive physiological Y axis is right to left. Figure VIII shows the relationships between the NASA vehicle terminology and the proposed physiological acceleration terminology.

For convenience in conversation, we accept the usage, "What is G_x?", for example, using the unit vector to represent the total vector, instead of the more precise, "What is the physiological acceleration along X?". We also tend to verbalize G_x as "gee ex" rather than as "gee sub ex," and in fact find it convenient in typing to write Gx, instead of the subscript notation.



Description		Symbol	
Aircraft	Physiological	Aircraft	Physiological
Linear Acceleration Modes			
Forward	Supine G	$+a_x$	$+N_1 G_X$
Backward	Prone G	$-a_x$	$-N_1 G_X$
Upward	Positive G	$-a_z$	$+N_3 G_Z$
Downward	Negative G	$+a_z$	$-N_3 G_Z$
Straight and level flight at constant speed		$a_z = 0;\ n_z = 1g$	$N_3 G_Z = 1 G_Z$
To right	Lateral G	$+a_Y$	$+N_2 G_Y$
To left	Lateral G	$-a_Y$	$-N_2 G_Y$
Angular Acceleration Modes			
Roll right	The heart rolls left	$+\dot{p}$	$+N_4 \ddot{R}_X$
Pitch up	The heart pitches down	$+\dot{q}$	$+N_5 \dot{R}_Y$
Yaw right	The heart yaws left	$+\dot{r}$	$-N_6 \dot{R}_Z$

Figure VIII. Relationship of physiological accelerations to description of acceleration environment.

Table III, at the end of this section, compares a number of the acceleration terminologies. The aviation medicine verbal acceleration descriptions have to be read with care to distinguish action from reaction terminologies. Ejection may be said to involve seat-to-head acceleration (i.e., action or displacement of the seat) but expose the pilot to head to seat forces (i.e., reaction, or positive G). Whereas one talks (Ruff and Strughold, 1939) about back to chest acceleration in catapulting (the action), the centrifuge simulation involves chest to back centrifugal acceleration (reaction). For the rocket track work, Dr. Stapp adopted the terminology of the "forward facing" experience, to represent this orientation of the subject when he hit the water brakes of the track, which we would now call $-G_X$. Clarke and Bondurant speak of "forward"

acceleration (action), and Eiband of "sternumward" acceleration (action) for aircraft catapulting. The origins of the test pilot's nomenclature of eyeball motion, first learned by us from test pilots of the NASA Ames Research Center, and the origins of the nautical terminology of surge, heave, and sway, have not yet been traced by us, although Doolittle (1925) does mention eyeball motion in a pull-up. The old term "transverse acceleration" has been used both for accelerations on the front-back axis and for accelerations on the side to side axis (Armstrong 1939). We follow others in recommending that "transverse acceleration" be used for accelerations along the X axis (front to back) and "lateral acceleration" for accelerations along the Y axis (side to side), if it is desired to use these more general words.

Aerodynamicists describe the total load normal to the airplane axis (along the Z axis), including both displacement and gravitational stresses, as the "normal load," with the symbol n_z (or n_N; see Smedal et al. 1960) to distinguish this from the Z axis displacement accelerations a_z. The convention is to call the normal load positive for a pull-up. The normal load is approximately measured by the instrument panel accelerometer. The X and Y axis accelerometer readings may be described by n_x (positive when the airplane moves forward,) and n_y (positive, when the airplane moves to the right), without correcting these readings for the contributions of the gravitational components, as is required to give the displacement accelerations a_x and a_y. The aerodynamic conventions do not include subscripts with the g unit. It is therefore important that one knows whether n_z or a_z is being discussed. It is suggested that the "normal load" terminology could be dropped, substituting the total reactive load or the physiological acceleration terminology, with unit vectors G_X, G_y, and G_Z for the raw accelerometer readings, thereby retaining the unit vectors g_x, g_y and g_z for the true displacement accelerations.

TABLE III

Acceleration Terminologies
(For a Pilot Sitting Upright in an Aircraft)

NASA (aircraft action)	Proposed here (heart reaction) (unit vector)	Pilots (reaction)	Old aviation terminology (reaction)	Stapp	Clarke & Bondurant (action)	Eiband (action)	Navy
$+a_x$ (catapulting)	$+G_x$ (heart moves toward the back)	eyeballs in	chest-to-back front-to-back supine	backward facing	forward	sternum-ward	surge
$-a_x$ (arresting)	$-G_x$ (heart moves toward the front)	eyeballs out	back-to-chest prone	forward facing	backward	spine-ward	
$+a_y$ (yaw right)	$+G_y$ (heart moves left)	eyeballs left	lateral		rightward		sway
$-a_y$ (yaw left)	$-G_y$ (heart moves right)	eyeballs right	lateral		leftward		
$+a_z$ (push-over)	$-G_z$ (heart moves up)	eyeballs up	negative G head-to-seat		footward	tailward	
$-a_z$ (pull-up)	$+G_z$ (heart moves down)	eyeballs down	positive G seat-to-head		headward	headward	heave

VI. The Origin of The Acceleration Axis System

The origin of the axis system may be of concern as measurements are refined, for whenever the subject has an angular acceleration and/or angular velocity, different parts of even a rigid body will experience different linear accelerations, although all experience the same angular velocities and accelerations. For example, a subject rotating steadily about an axis 20 ft. from his feet in a "seated" position in the plane of rotation with his head toward the axis, has 20 per cent more radial acceleration at his feet than at his head. In larger centrifuges and in most of the present or proposed air and space flight maneuvers, linear acceleration gradients rarely exceed 0. 2G per foot at the subject, and linear accelerometers in back of the seat are used as measures of the subject's accelerations. It is common practice, even in centrifuge studies, to ignore these linear-acceleration gradients by not specifying the angular velocities and accelerations and the point at which the linear accelerations were measured. As we refine our biological data and interpretations, it is urged that angular velocities and accelerations and the origin of the linear-acceleration axes always be specified.

In previous work we have considered the Z axis to be parallel to "the spine"--and have ignored the 5° or 10° uncertainties introduced in referencing this rather non-linear structure. We feel that the origin of the acceleration axes should be anatomically precise and related to body structures of limited movement. Thus the body "center of gravity, " which for a seated subject may be a couple of inches in front of the navel, is not a good reference. The anterior surface of the eye may be suitable for some work, but is not good for general use because of effects of head motion. The heart also may be of concern during acceleration, and so has been suggested as the axes origin, but it is an internal organ several inches across and not certain in location which changes under acceleration. The navel likewise is readily displaced. On the other hand the anterior (craniad) points on the iliac crests, the suprasternal notch, and the dorsal surface of the dorsal spine of the last cervical vertebra are quite precise anatomically.

We therefore suggest an origin for the acceleration axes of mammals at a point within the body half way between the anterior (craniad) points on the iliac crests, which are on the Y axis. The Z axis passes through this origin and through a point half way between the suprasternal notch and the dorsal surface of the dorsal spine of the last cervical vertebra. The X and Y axes are mutually perpendicular to this Z axis. For most acceleration studies, it is

considered adequate to specify the geometrical relationships between the subject and linear accelerometers located within a foot or two of the body, and to specify the angular velocities and angular accelerations of the seat; until our biology is more precise, a transformation of the measured accelerations to the proposed biological axes origin does not seem required. Note that if angular velocities are zero at the start of an acceleration period, integration of the angular accelerations can provide the angular velocities needed for calculations to displace the reference point of linear accelerations. For convenience in making such calculations, however, and to reduce errors in integrating angular acceleration, it is suggested that physiological acceleration environments be specified by time histories of three linear acceleration components, three angular acceleration components, and three angular velocity components, with the reference origin of the linear accelerations being specified (with respect to the body). For the aerodynamicist to compute displacement accelerations from flight measurements, he must also record angular attitudes (Euler angles) or compute these by integration of angular velocities.

For some studies, for example of vestibular functions, it will be desirable to reference the accelerations to the head, which may have fixed or varying roll, pitch and yaw angles with regard to the body. A possible head-axis system would have the Y axis passing between the external auditory meatuses, with the origin in the center. The X axis would pass from the ventral medial limit of the nasal bone to this origin. The Z axis would be mutually perpendicular to these. We have not yet located the expectedly more thorough anatomical studies concerned with body-axis systems.

VII. Angular Velocity and Angular Acceleration

Whenever a body is rotating with angular velocity ω (in rad./sec.), a linear acceleration (centrifugal acceleration) is developed along the radius r (in feet) given by $a_{radial} = \frac{r\omega^2}{g}$, in G units, with the reactive load acting away from the axis of rotation (g being the acceleration of gravity, 32.2 ft./sec.^{2}). If there is also an angular acceleration $\dot{\omega}$ (in radians/sec.^{2}), a linear acceleration is developed tangent to the arc of rotation, given by

$$a_{tangential} = \frac{-r\dot{\omega}}{g}$$ in G units, with the reactive load acting opposite in sign to the direction of accelerating displacement.

It has been a convention of the aerodynamicists to describe attitude angles in degrees but, in order to use the above equations

without the conversion factor from degrees to radians, to describe angular velocities in radians/sec. and angular accelerations in radians/sec.^{2}. To insure ease in discussing programs of centrifuge simulation of flight accelerations with aerodynamicists, we have found it convenient to accept similar conventions of units. We however suggest the symbol R ("rotation") for the unit vector of 1 radian/sec. of angular velocity, and $\dot{R}$ for the unit vector of 1 radian/sec.^{2} of angular acceleration, with subscripts being used to indicate the axis of rotation. The older terminology, for example, of "5 radians/sec. about the X axis" then becomes "$5R_x$", and "7 radians/sec.^{2} about the Y axis" then becomes "$7\dot{R}_y$". Franks (1960) has suggested the unit A, with appropriate subscripts, for angular acceleration measured in degrees/sec.^{2}.

The aerodynamicists in mathematical derivations use the symbols p, q, and r for angular velocities, and $\dot{p}$, $\dot{q}$, and $\dot{r}$ for angular accelerations about the X, Y, and Z axes respectively, the positive directions being indicated by the "right-hand rule," that is if the right hand is placed so that the thumb is along the positive direction of the axis, the positive direction of rotation is indicated by the fingers, moving from palm to finger tips (Figure VI). In our initial terminology proposal (Clark and Crosbie, 1959), we suggested the use of "physiological p, q, or r," or "physiological $\dot{p}$, $\dot{q}$, or $\dot{r}$" for the values of concern, with the mathematical derivation being prefaced with the note that all symbols represent physiological, i.e. reactive, values. In daily usage, however, it is acceptable to say, for example, "What R_y do you have?" instead of "What physiological q do you have?", in spite of the awkwardness of the reply "My R_y is $-2R_y$." The physiological angular acceleration modes are presented in Figure VII.

It is emphasized that the physiological rotation values represent reactive responses. Thus if a dancer started a spin (pirouette) to the left at an angular acceleration of 5 rad./sec.^{2}, the heart would rotate (yaw) in the chest to the right with respect to the skeleton, and the physiological angular acceleration would be $+5\dot{R}_z$, positive by the right-hand rule applied to the positive (downward) physiological Z axis. Likewise the dancer's angular velocity might reach 10 rad./sec. to the left, for which the physiological designation would be $+10R_z$ for this direction of rotation with initial heart yaw to the right within the skeleton. The vehicle (action) and physiological (reaction) angular acceleration relationships are presented in Figure VIII.

VIII. Multi-Component Accelerations

When a resultant acceleration vector makes an angle with the body axes, usual procedure is to give the magnitudes of the components along the body axes, then possibly to give the magnitude of the resultant. Angles between the resultant and the axes may be given, but a convention has not been established for presenting these angles. Hagenwald (1957), describing acceleration effects in the median sagital plane (XZ plane), proposed a terminology involving the resultant G and the angle in this plane.

Byford notes the possibility of specifying the resultant and its three direction cosines, or using cylindrical or spherical polar coordinates. In analogy to the use in electrical engineering of the notation $E \angle\theta$ for an amplitude and phase angle, we propose the notation NG/ (azimuth, altitude) for a resultant acceleration vector, measuring azimuth from the positive X axis or back direction, with positive angles for clockwise rotation as seen from the top, and measuring altitude from the horizontal plane, positive when along the positive Z axis or downward. Thus a reentry of a low lift vehicle at $14G/180^{\circ}, 45^{\circ}$, would cause the heart to be thrown forward and downward, with components of $-10G_x$ and $+10G_z$. Table IV gives other examples of this proposed terminology for a resultant acceleration vector.

TABLE IV

Resultant Physiological Acceleration Terminology

Single Component	Resultant Vector Terminology NG/azimuth, altitude
$+3\ G_x$ (catapult)	$3G/0^{\circ}, 0^{\circ}$
$-4\ G_x$ (arrested landing)	$4\ G/180^{\circ}, 0^{\circ}$
$+1\ G_y$ (aircraft right yaw, heart moves left)	$1\ G/90^{\circ}, 0^{\circ}$
$-1\ G_y$ (aircraft left yaw, heart moves right)	$1\ G/-90^{\circ}, 0^{\circ}$
$+7\ G_z$ (pull-up)	$7\ G/0^{\circ}, 90^{\circ}$
$-2\ G_z$ (push-over)	$2\ G/0^{\circ}, -90^{\circ}$

NG/(azimuth from +X or back direction, positive clockwise from the top; altitude from the horizontal plane, positive along +Z or downward.)

IX. Accelerations Varying in Time

To describe accelerations varying in time, the most detailed method is to show the "acceleration time histories," or graphs of the accelerations versus time. Usual procedure has been to show the varying acceleration components, although in the case of a vehicle accelerating with a slowly varying resultant magnitude but oscillating attitude angles it may be more readily visualized to show time histories of resultant acceleration magnitude and its azimuth and altitude. For acceleration time histories of mathematically simple wave form, the description may be an equation instead of a graph. For oscillating accelerations of complex wave form varying over long periods, it may be helpful to speak of the acceleration exposure in terms of an "rms. acceleration," obtained by determining the square root of the mean of the squares of the instantaneous accelerations. For an aircraft flying at approximately a constant altitude in turbulent air, for example, the mean displacement acceleration is Og but the rms. acceleration (in severe turbulence) may be 0.5g, to give a physiological acceleration of 1 ± 0.5 rms G_Z. In predicting human tolerance, it is important to know the frequencies of the oscillating accelerations; a frequency distribution for the rms. amplitudes may be more directly useful than the acceleration time histories (Goldman and von Gierke, 1960). An extension of this approach is the "power spectral density" description of accelerations which may be described by "stationary random series." (Wiener, 1950), when the phase relationships between the various frequency components of the acceleration pattern are varying randomly in time. To help insure proper utilization of these acceleration data reduction techniques, it is recommended that sample acceleration time histories be presented along with the reduced data.

X. Coriolis Accelerations

When a body moves with a velocity V with respects to its near surroundings within a coordinate system or structure which is rotating at an angular velocity ω, departure of the path of the moving body from the path expected if the coordinate system were not rotating may be interpreted as the effect of a "Coriolis acceleration," 2ω XV, acting on the moving body. The disorienting effects of head motion while in a turning aircraft (Head, 1919; Wulfften-Palthe, 1922) were interpreted by Schubert (1931, 1935) as a manifestation of a Coriolis acceleration effect. (See also von Diringshofen, 1934)

The Coriolis effects of such head motions are to introduce couples of force acting on the semicircular canals and endolymph (Clark, 1960; Gray et. al, 1961) giving illusions of rotation about

the axis specified by the vector product $\omega \times \omega_h$, where ω is the angular velocity of the body and near surroundings and ω_h is the angular velocity of the head. The Coriolis illusion threshold is near 0.06 rad.^{2}/sec.^{2} (for the vector product $\omega \times \omega_h$), and the nausea threshold for the Coriolis type of stimulus is near 0.6 rad.^{2}/sec.^{2} for one subject (Clark, 1960). It may be convenient to designate head angular velocities by the value NR_h, and head angular accelerations by $N\dot{R}_h$, with additional subscripts indicating the roll (X), pitch (Y) or yaw (Z) axis involved. The nod "yes" for example, may involve a pitch down head motion of $-2R_{hy}$ (2 radians per second of the head about the Y axis). Note that the eyeballs initially rotate upward (pitch up) in the head, from inertia, as the head swings downward. This eyeball motion is negative about the physiological Y axis.

XI. Conclusions

This report has reviewed certain acceleration concepts and terminologies. The need is evident for a physiological acceleration terminology which is mathematically precise and is distinguishable from the flight vehicle displacement acceleration terminology, which does not include the reactive effects of resisting the gravitational attraction. Such a physiological acceleration terminology is proposed.

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ACCELERATION ENVIRONMENTS PERTINENT TO AEROSPACE MEDICAL RESEARCH

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Examination of a typical space flight originating from any point on the earth and returning to earth immediately limits any discussion of the acceleration effects to considerations of specific problem areas. This approach lends itself to the discussion of such an event by phases: Phase I. Launch (boost), Phase II. Orbit (flight), Phase III. Reentry, Phase IV. Recovery (high-drag system only), and Phase V. Landing.

Unfortunately, the acceleration situation is complicated by vehicle configuration. There are basically two extremes of vehicle configuration, the high drag (blunt-body type such as the Mercury Capsule) and the high lift (winged vehicle such as Dyna Soar). Needless to say, there can be many degrees of variation within these two extremes which would necessitate an almost infinite number of acceleration considerations.

Escape will be considered separately after the complete discussion of all the phases, due to the fact that escape can occur during any phase and produces complex or compounded acceleration factors depending on when it occurs and what method is used.

Phase I: Launch Accelerations

Launch accelerations are a function of flight-vehicle weight related to booster thrust. The type of flight vehicle (high drag or high lift) has minimal effect on launch acceleration profile. There is a constant requirement to compromise the ideal acceleration situation with the booster state-of-the-art capability. Ideally, it would be best for man in the system if accelerations could be maintained at low levels. Miller et al[1] demonstrated that man can readily tolerate and function well for 60 minutes at 3 G. This not only exceeds orbital velocity, but is well beyond escape velocity.

Unfortunately no such booster capability exists, and the nuclear or ion propulsion type systems that could provide this capability are still years away.

Therefore, we are presently confined to considering such booster systems as Atlas, Titan, Saturn, and Nova. So far, experience proves that all allowable payload weight will be used. No one has indicated any tendency to relax this approach. Therefore, the acceleration profile can be described with more than average accuracy and even more assurance.

First-stage launch accelerations are naturally the largest in G-magnitude, due to the fact that the densest part of the atmosphere is traversed during this phase of the flight. The onsets of the accelerations are low and of insignificant physiological concern. Therefore, it can be stated that the Atlas or Titan can produce acceleration forces in the order of a peak of 16 G, being above 10 G for 40 seconds with as much as 20 to 30 seconds getting to and from 10 G. With adequate consideration of human tolerance and function, the acceleration profile can be engineered to more reasonable limits of about an 8-to-9 G Peak, being above 6 G for 60 to 80 seconds with a total duration of 160 to 180 seconds.

Bates[2] reports that we can expect a Time/G history from Nova of about 7 G for 180 to 200 seconds, and 5 G for 300 to 320 seconds from Saturn. The trend is in the right direction and these latter two boosters can be considered in the transition zone from the high G-short duration to the ideal low G-long duration capability.

Second and/or third-stage boosters should not present any acceleration problems. Onsets will naturally be higher due to the absence of any appreciable drag in the near-vacuum environment in which they will operate. These onsets of acceleration should be well within experienced limits. The unanswered and debatable problem is acceleration "offset" at first and/or second-stage burn-out. (It is the author's opinion that the physiological effect of "offset" will be equal in effect to that of "onset." Studies involving high-acceleration onsets indicate that minimal concern is necessary for short-duration-G exposures.)

Phase II: Orbit (Flight)

The major acceleration aspect of orbit or flight is in the sub-gravity or reduced-G-field environment. Although this can be technically considered a reduced acceleration environment the importance of this area demands special consideration and is completely described by Gerathewohl.[3]

The minor accelerations produced by reaction controls for vehicle orientation during orbital flight are of a very low order of G-magnitude and are not considered to have any physiological significance per se, although superimposition of even the small accelerations for space navigation on the weightless state of space flight may possibly have an effect on vestibular function due to the stabilized adjustment of this apparatus to the reduced-G environment which might then be hyperreactive to small acceleration forces.

Phase III: Reentry

During reentry we must again consider the vehicular configuration in order to describe the acceleration environment. For the high-drag, low-lift vehicle, high-G loads for short durations must be experienced. Hardy[4] has calculated that a blunt body on an uncontrolled reentry from escape velocity could obtain a peak of 300-400 G. Based on known human tolerance to accelerative forces, this would impose lethal loads on the human organism. The maximum experimental exposure to short duration high G loading was experienced by Beeding[5] in 1958. This was +82.6 G with a calculated 3,826 G/sec/sec onset with a total duration of .04 seconds (measured on the chest accelerometer, rearward facing) in a seat with a 10^{o} tilt rearward from the vertical back position. The medical interpretation of his condition following this exposure can be summarized as follows:

Shock, reversible
Lumbar compression (no fracture)
Contusion--greater curvature of the stomach
Returned to duty in 3 days--rode the DAISY sled again in less than three months

No protective measures for G loads of this magnitude or higher are known today. This would demand a design requirement for space vehicles that will provide at least tolerable reentry G loads, or preferably G-loads that will permit vehicle operation and control by the pilot.

High-drag systems reentering from orbit can be designed to experience 12 to 16 G for about 10 seconds as the maximum, with a gradual build up to peak G over 30 to 50 seconds. This requires exacting control over the reentry angle which is partly a function of vehicle configuration and heat-shield design. In contrast to the high-drag vehicle, the high-lift design, such as Dyna Soar, will produce negligible G loads provided the pilot executes a well-controlled reentry flight maneuver.

Whether or not the effect of the reentry G following the subgravity of orbit belongs in the discussion of weightlessness, it would be remiss to omit it at this point. Von Beckh[6] has demonstrated a lowered blackout tolerance for human subjects following very brief (25 seconds) exposures to subgravity conditions which were almost zero G. If this information is indicative of the effect of zero G on the cardiovascular systems response, then the further study of this problem area is indicated. It is intriguing to try and postulate what will happen after hours or days of orbit in zero-G conditions when the pilot is subjected to the 4 G's of reentry in a high-lift system or the 12-16 G's in a high-drag system.

Phase IV: Recovery

The Recovery Phase is only applicable to the high-drag system, which must be decelerated prior to its relatively uncontrolled landing. Several methods have been proposed for this phase such as balloons, extendable flaps, telescopic rotor blades, and the parachute. So far, reliability and experience have made the use of the parachute the accepted method. The G forces experienced during parachute deployment and inflation are relatively low, 9 to 11 G, and are only 2-3 seconds in duration.

The high lift vehicle eliminates this phase due to its aerodynamic configuration permitting conventional flight after reentry into the atmosphere.

Phase V: Landing

The Landing Phase, acceleratively speaking, is pertinent to only the high drag system. As described above, it is an uncontrolled landing to the extent that the vehicle merely lands at the descent rate established by the parachute system and at a drift rate due to the wind conditions in the landing area. This situation produces a new acceleration problem, specifically "oblique G." Under calm conditions, it is estimated that the vehicle will impact water at a peak of about 40 G, with onsets of 6,000 to 8,000 G/sec/sec, lasting less than one second. For land impact, the estimate is a peak of 60 G, with onsets of 8,000 to 12,000 G/sec/sec. Duration would be the same or even shorter (less than 0.5 sec.), depending on what type of landing-impact attenuating device may be employed. If there is a direct relationship between G-onset and peak-G tolerance (i.e. the higher the onset the lower the G threshold), then this latter situation, land impact, is in a potentially injurious acceleration-force area. If one were to superimpose a wind velocity of 10 knots in the horizontal vector, the resultant G

load in an oblique vector could be lethal. The area of oblique-G acceleration and its physiological effect on man is almost totally uninvestigated, and poses a new area for future acceleration research.

The high-lift systems are designed to land on designated sites, either prepared strips or natural areas such as salt flats, in the same manner as the X-15. No unusual acceleration effects are anticipated, even though landing speeds may well be high in comparison to conventional aircraft.

Escape

As mentioned in the beginning of this discussion, the escape accelerations cannot be categorized due to the fact that there are many methods, involving different systems, and escape can occur at any time. It can be assumed that the worst situation from an acceleration standpoint would be the use of additional thrust to separate the pilot and his system from the booster at some point during launch while still within the atmosphere, but after the system has attained fairly high velocity. Such a situation is calculated to produce 22 to 26 G at an onset of 2, 000 to 4, 000 G/sec/sec for 8-12 seconds.

Such a situation would be most likely to have vibrations and oblique vectors. Vibrations (oscillations) occur during launch and reentry. Launch vibrations, associated with booster thrust, are high-frequency, low-amplitude, whereas reentry vibrations are low-frequency, high-amplitude. Considering the system damping, the launch vibrations reaching the pilot can range from 11 to 16 cps and only plus-to-minus two to three degrees. The reentry vibrations can be expected to range from two to four cps and plus-to-minus seven to nine degrees.

This too is an area of acceleration which requires further research. Von Gierke[7] has reported some interesting findings in the study of human tolerance to vibration and the natural frequency responses of several body systems and/or organs. The additional need for the study of combined acceleration forces (vibrations superimposed on linear accelerations) is a function of space flight even for high-lift systems which are estimated to experience vibrations during reentry.

An inseparable corollary to the entire field of acceleration research is the urgent need for better and improved methods of instrumentation, mainly of the test subject's physiological parameters, and also of the physical forces as they are transmitted to and reflected by the human structure and systems.

The foregoing is an attempt to present briefly the major acceleration patterns anticipated in manned space flight, and to identify relatively unknown areas of human acceleration tolerance demanding the attention of research scientists in this field.

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